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A psychophysical investigation of quantum cognition: An interdisciplinary synthesis

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Marie-Curie Fellow

A psychophysical investigation of quantum cognition: An interdisciplinary synthesis

RESEARCH & INNOVATION

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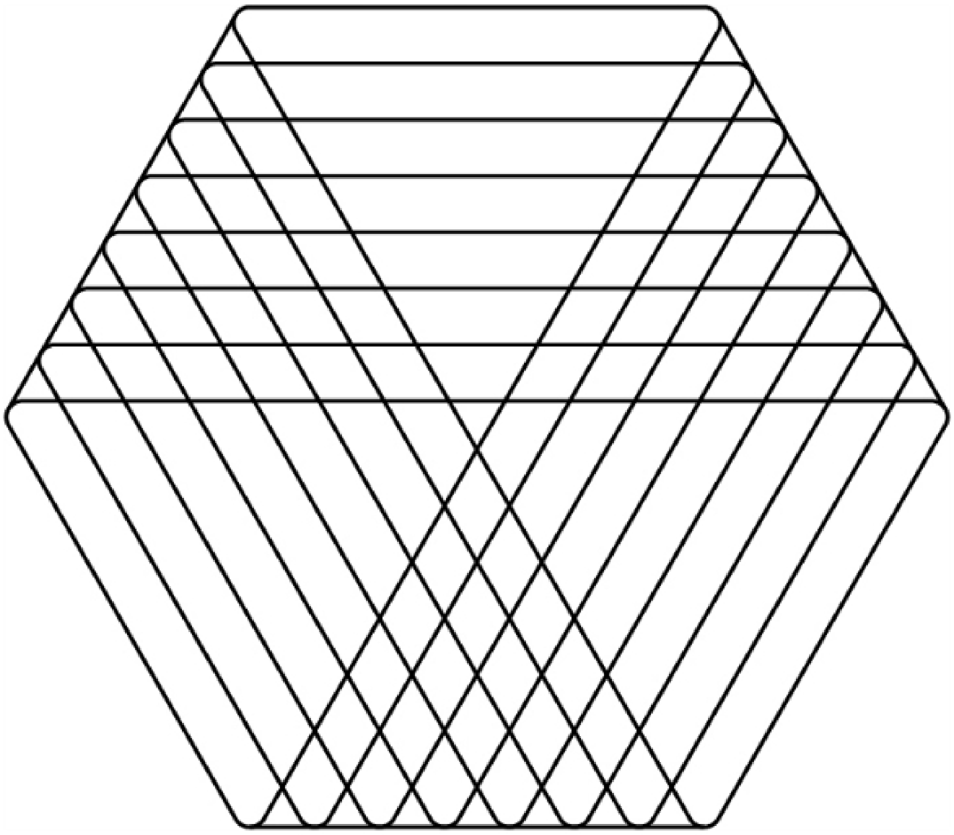

A psychophysical investigation of quantum cognition:

An interdisciplinary synthesis

by Christopher B. Germann

A thesis submitted to the University of Plymouth

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Doctor of Philosophy

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Indagate Fingite Invenite (Explore, Dream, Discover)

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Signed: ______________________________

Date: ______________________________

Prefix: Interpretation of the cover illustration

The cover of this thesis depicts a variation of Möbius band which has been eponymously named after the German astronomer and mathematician August Ferdinand Möbius. An animated version of the digital artwork and further information can be found on the following custom-made website:

URL: http://moebius-band.ga

The Möbius band has very peculiar geometrical properties because the inner and the outer surface create a single continuous surface, that is, it has only one boundary. A Gedanken-experiment is illustrative: If one imagines walking along the Möbius band starting from the seam down the middle, one would end back up at the seam, but at the opposite side. One would thus traverse a single infinite path even though an outside observer would think that we are following two diverging orbits. We suggest that the Möbius band can be interpreted as a visual metaphor for dual-aspect monism (Benovsky, 2016), a theory which postulates that the psychological and the physical are two aspects of the same penultimate substance, i.e., they are different manifestations of the same ontology. Gustav Fechner (the founding father of psychophysics) was a proponent of this *Weltanschauung*, as were William James, Baruch de Spinoza, Arthur Schopenhauer, and quantum physicists Wolfgang Pauli and David Bohm, *inter alia*. The nondual perspective is incompatible with the reigning paradigm of reductionist materialism which postulates that matter is ontologically primary and fundamental and that the mental realm emerges out of the physical, e.g., epiphenomenalism/evolutionary emergentism (cf. Bawden, 1906; Stephan, 1999)). The nondual perspective has been concisely articulated by Nobel laureate Bertrand Russel:

"*The whole duality of mind and matter [...] is a mistake; there is only one kind of stuff* *out of which the world is made, and this stuff is called mental in one arrangement, physical in the other*." (Russell, 1913, p.15)

From a psychophysical perspective it is interesting to note that quantum physicist and Nobel laureate Wolfgang Pauli and depth psychologist Carl Gustav Jung discussed dual-aspect monism extensively in their long-lasting correspondence which spanned many years. In particular, the "Pauli-Jung conjecture" (Atmanspacher, 2012) implies that psychological and physical states exhibit complementarity in a quantum physical sense (Atmanspacher, 2014b; Atmanspacher & Fuchs, 2014). We suggest that the Möbius band provides a "traceable" visual representation of the conceptual basis of the dual-aspect perspective. A prototypical Möbius band (or Möbius strip) can be mathematically represented in three-dimensional Euclidean space. The following equation provides a simple geometric parametrization schema:

$$x(u,v) = (3 + \frac{v}{2}\cos\frac{u}{2})\cos u$$

$$y(u,v) = (3 + \frac{v}{2}\cos\frac{u}{2})\sin u$$

$$z(u,v) = \frac{v}{2}\sin\frac{u}{2}$$

where $0 \leq u < 2\pi$ and $-1 \leq v \leq 1$. This parametrization produces a single Möbius band with a width of 1 and a middle circle with a radius of 3. The band is positioned in the *xy* plane and is centred at coordinates (0, 0, 0). We plotted the Möbius band in R and the associated code utilised to create the graphic is based on the packages "`rgl`" (Murdoch, 2001) and "`plot3D`" (Soetaert, 2014) and can be found in Appendix A1. The code creates an interactive plot that allows to scale and rotate the Möbius band in three-dimensional space.

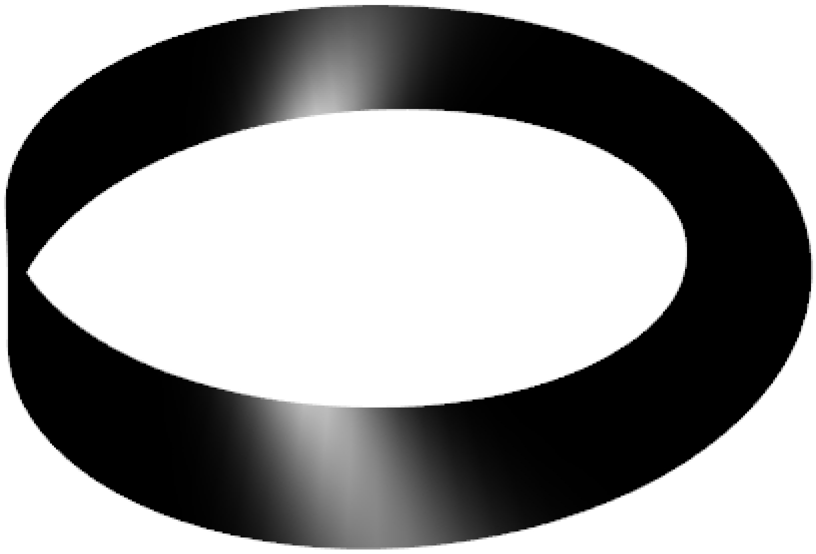

Figure 1. Möbius band as a visual metaphor for dual-aspect monism.

The cover image of this thesis is composed of seven parallel Möbius bands (to be accurate these three-folded variations of the original Möbius band). It is easy to create a Möbius band manually from a rectangular strip of paper. One simply needs to twist one end of the strip by 180° and then join the two ends together (see Starostin & Van Der Heijden, 2007). The graphic artist M.C. Escher (Crato, 2010; Hofstadter, 2013) was mathematically inspired by the Möbius band and depicted it in several sophisticated artworks,e.g., “Möbius Strip I” (1961) and “Möbius Strip II” (1963).

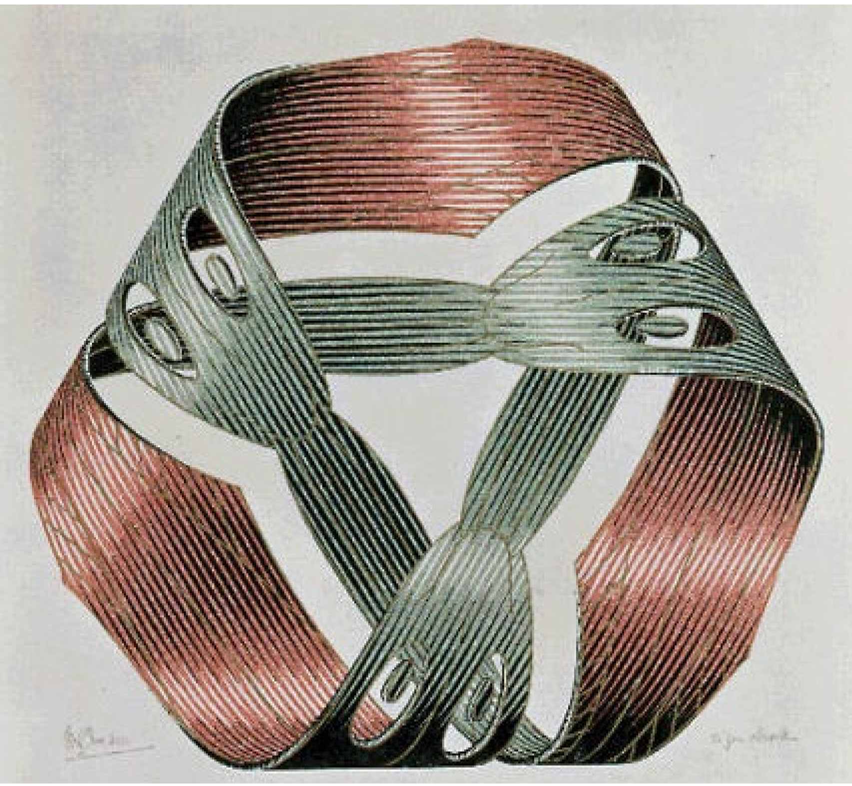

Figure 2. “Möbis Strip I” by M.C. Escher, 1961 (woodcut and wood engraving)

A recent math/visual-arts project digitally animated complex Möbius transformations in a video entitled “Möbius Transformations Revealed” (Möbiustransformationen beleuchtet). The computer-based animation demonstrates various multidimensional Möbius transformation and shows that “moving to a higher dimension reveals their essential unity”[1] (Arnold & Rogness, 2008). The associated video[2] can be found under the following URL:

http://www-users.math.umn.edu/~arnold/moebius/

[1] Interestingly, a similar notion forms the basis of “Brane cosmology” (Brax, van de Bruck, & Davis, 2004; Papantonopoulos, 2002) and its conception of multidimensional hyperspace. Cosmologists have posed the following question: “Do we live inside a domain wall?” (Rubakov & Shaposhnikov, 1983). Specifically, it has been argued that “(light) particles are confined in a potential well which is narrow along N spatial directions and flat along three others.”

[2] The video is part of a DVD titled “MathFilm Festival 2008: a collection of mathematical videos” published by Springer (Apostol et al., 2008) which is available under the following URL: http://www.springer.com/gb/book/9783540689027
Moreover, the computer animation was among the winners of the “Science and Engineering Visualization Challenge” in 2007.

Additionally, we integrated a high-resolution version of the video in our website, together with supplementary background information:

http://irrational-decisions.com/?page_id=2599

Mathematics and particularly its subordinate branch geometry have always been regarded as cognitive activities which enable access to transcendental/metaphysical realms (e.g., for instance Pythagoras's theorem and Plato's transcendent forms) and there is a longstanding interrelation between geometry, mathematics, and mysticism (e.g., sacred geometry, Fibonacci numbers, etc.) as has been pointed out by eminent mathematicians who argue for the pivotal importance of mystical influences in the history of mathematics (e.g., Abraham, 2015, 2017). For instance, it has been argued that there is a close relation between geometry, space-time, and consciousness (Beutel, 2012), a perspective which can be found in many religions and ancient knowledge traditions, e.g. Yantra (Sanskrit: यन्त्र) and Mandala (मण्डल) in ancient Indian schools of thought (also found in Buddhism*, inter alia*). Moreover, geometry was pivotal for the progress of the exact sciences like cosmology and astronomy. For instance, when the Lutheran astronomer Johannes Keppler's published his "*mysterium cosmographicum*" at Tübingen in 1596, he based his theory on five Pythagorean polyhedra (Platonic solids) which he conjectured form the basis of the structure of the universe and thus realise God's ideas through geometry (Voelkel, 1999).

The geometry of the Möbius band has broad interdisciplinary pertinence. Besides its contemporary relevance in the sciences like chemistry (e.g., "Möbius aromaticity" (Jux, 2008), "Möbius molecules" (Herges, 2006)), mathematics (Waterman, 1993), and physics (Chang et al., 2010)) "the curious band between dimensions" has significance for perceptual psychology. For instance, it has been argued that "we can also use its dynamics to reveal the mechanisms of our perception (or rather, its deceptions as in the case of optical illusions) in an augmented space-time." (Petresin & Robert, 2002)

To sum up this annotation, the interpretation of the Möbius band has multifarious semantic/hermeneutic layers and provides an apt visual primer for the concept of psychophysical complementarity which will be discussed in greater detail in the subsequent thesis, particularly in the context of nonduality and quantum cognition.

Acknowledgements

First, I would like to acknowledge my supervisor Prof. Chris Harris who gave me the "cognitive liberty" to engage in interdisciplinary, innovative, and unconventional research. He kindly invited me to pursue this prestigious Ph.D. as a Marie-Curie Fellow. Moreover, I would like to express my gratitude to Prof. Geetika Tankha who proficiently supported my experimental studies during my secondment at Manipal University Jaipur in India.

Furthermore, I would like to thank Dr. Christopher Berry and Prof. Harald Walach for adopting the role of the internal and external examiner, respectively.

Finally, I would like to remember Dr. Martha Blassnigg (*1969; †2015) who was a special and truly gifted scholar in many respects. She had a deep interest in holistic approaches to the mind-body correlation, a theme which is of great pertinence for the thesis at hand.

The primary impetus for the present interdisciplinary thesis is derived from a personal initiatory nondual experience of "unity consciousness" (nondual consciousness). This profound topic has recently received great attention in the pertinent contemporary psychological and neuroscientific literature even though it has been discussed by philosophers of mind for time immemorial. Hence, the topic of nonduality is of great psychological importance and it intersects with various disciplines such as neurochemistry, quantum physics, and various ancient eastern knowledge traditions, *inter alia*. It is thus a truly interdisciplinary topic with great pragmatic importance for the evolution of science and humanity as a species.

Special thanks are directed towards the Sivananda Yoga Vedānta Ashram in Kerala in South India. I had the great privilege to take part in a knowledge tradition which dates back several thousand years. My experiences in this centre for spiritual growth and

learning further strengthened my conviction in the importance of ethics and morality and specifically purity of thought, word, and action. Yoga is a truly psychologically transformative practice and Swami Sivananda's dictum "an ounce of practice is worth tons of theory" illustrates the importance of first-person phenomenological experience for which there is no substitute. One of the essential teachings of yoga is that the individual must change before the world can change, viz., the microcosm and the macrocosm are intimately interrelated. Consequently, self-reflection, self-actualisation, and self-realisation (in the Maslowian sense) are of utmost significance. Moreover, Advaita Vedānta emphasises "unity in diversity", a philosophical perspective which has great relevance for the thesis at hand due to its pertinence for a nondual conceptualisation of reality.

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- Animated version of the Möbius band which constitutes the cover image:
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- Online repository associated with this thesis containing all datasets:
  http://irrational-decisions.com/phd-thesis/
- Literature review on quantum cognition (HTML format):
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- Möbius band transformations:
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Author: Christopher B. Germann

Title: A psychophysical investigation of quantum cognition: An interdisciplinary synthesis

Abstract

Quantum cognition is an interdisciplinary emerging field within the cognitive sciences which applies various axioms of quantum mechanics to cognitive processes. This thesis reports the results of several empirical investigations which focus on the applicability of quantum cognition to psychophysical perceptual processes. Specifically, we experimentally tested several *a priori* hypotheses concerning 1) constructive measurement effects in sequential perceptual judgments and 2)noncommutativity in the measurement of psychophysical observables . In order to establish the generalisability of our findings, we evaluated our prediction across different sensory modalities (i.e., visual versus auditory perception) and in cross-cultural populations (United Kingdom and India). Given the well-documented acute "statistical crisis" in science (Loken & Gelman, 2017a) and the various paralogisms associated with Fisherian/Neyman-Pearsonian null hypothesis significance testing, we contrasted various alternative statistical approaches which are based on complementary inferential frameworks (i.e., classical null hypothesis significance testing, nonparametric bootstrapping, model comparison based on Bayes Factors analysis, Bayesian bootstrapping, and Bayesian parameter estimation via Markov chain Monte Carlo simulations). This multimethod approach enabled us to analytically cross-validate our experimental results, thereby increasing the robustness and reliability of our inferential conclusions. The findings are discussed in an interdisciplinary context which synthesises knowledge from several *prima facie* separate disciplines (i.e., psychology, quantum physics, neuroscience, and philosophy). We propose a radical reconceptualization of various epistemological and

ontological assumptions which are ubiquitously taken for granted (e.g., naïve and local realism/cognitive determinism). Our conclusions are motivated by recent cutting-edge findings in experimental quantum physics which are incompatible with the materialistic/deterministic metaphysical *Weltanschauung* internalised by the majority of scientists. Consequently, we argue that scientists need to update their nonevidence-based implicit beliefs in the light of this epistemologically challenging empirical evidence.

CHAPTER 1. INTRODUCTION

We would like to set the stage for this thesis with a rather extensive[3] but highly apposite prefatory quotation from the great polymath William James who can be regarded as the founding father of American psychology. The following quote stems from the introduction of his essay entitled "The hidden Self" which was published in 1890: "*Round about the accredited and orderly facts of every science there ever floats a sort of dust-cloud of exceptional observations, of occurrences minute and irregular, and seldom met with, which it always proves less easy to attend to than to ignore. The ideal of every science is that of a closed and completed system of truth. The charm of most sciences to their more passive disciples consists in their appearing, in fact, to wear just this ideal form. Each one of our various 'ologies' seems to offer a definite head of classification for every possible phenomenon of the sort which it professes to cover; and, so far from free is most men's fancy, that when a consistent and organized scheme of this sort has once been comprehended and assimilated, a different scheme is unimaginable. No alternative, whether to whole or parts, can any longer be conceived as possible. Phenomena unclassifiable within the system are therefore paradoxical absurdities, and must be held untrue. When, moreover, as so often happens, the reports of them are vague and indirect, when they come as mere marvels and oddities rather than as things of serious moment, one neglects or denies them with the best of scientific consciences. Only the born geniuses let themselves be worried and fascinated by these outstanding exceptions, and get no peace till they are brought within the fold. Your Galileos, Galvanis, Fresnels, Purkinjes, and Darwins are always getting confounded*

[3] It is easy to misinterpret a quote when it is taken out of its associated context. We tried to circumvent this common scholarly fallacy by providing an exhaustive quotation, thereby significantly reducing the odds of committing hermeneutic errors.

and troubled by insignificant things. Anyone will renovate his science who will steadily look after the irregular phenomena. And when the science is renewed, its new formulas often have more of the voice of the exceptions in them than of what were supposed to be the rules. No part of the unclassed residuum has usually been treated with a more contemptuous scientific disregard than the mass of phenomena generally called mystical. Physiology will have nothing to do with them. Orthodox psychology turns its back upon them. Medicine sweeps them out; or, at most, when in an anecdotal vein, records a few of them as 'effects of the imagination' a phrase of mere dismissal whose meaning, in this connection, it is impossible to make precise. All the while, however, the phenomena are there, lying broadcast over the surface of history. No matter where you open its pages, you find things recorded under the name of divinations, inspirations, demoniacal possessions, apparitions, trances, ecstasies, miraculous healings and productions of disease, and occult powers possessed by peculiar individuals over persons and things in their neighborhood. […] To no one type of mind is it given to discern the totality of Truth. Something escapes the best of us, not accidentally, but systematically, and because we have a twist. The scientific-academic mind and the feminine-mystical mind shy from each other's facts, just as they shy from each other's temper and spirit. Facts are there only for those who have a mental affinity with them. When once they are indisputably ascertained and admitted, the academic and critical minds are by far the best fitted ones to interpret and discuss them - for surely to pass from mystical to scientific speculations is like passing from lunacy to sanity; but on the other hand if there is anything which human history demonstrates, it is the extreme slowness with which the ordinary academic and critical mind acknowledges facts to exist which present themselves as wild facts with no stall or pigeon-hole, or as facts which threaten to break up the accepted system. In psychology, physiology, and *medicine, wherever a debate between the Mystics and the Scientifics has been once for all decided, it is the Mystics who have usually proved to be right about the facts, while the Scientifics had the better of it in respect to the theories.* (James, 1890a, pp. 361–362)

James is very explicit when he emphasises the irrational reluctance of the majority of academic scientists to "face facts" when these are incongruent with the prevailing internalised paradigm. Thomas Kuhn elaborates this point extensively in his seminal book "The Structure of Scientific Revolutions" (T. Kuhn, 1970) in which he emphasises the incommensurability of paradigms. Abraham Maslow discusses the "Psychology of Science" in great detail in his eponymous book (Maslow, 1962). Maslow formulates a quasi-Gödelian critique of orthodox science and its "unproved articles of faith, and taken-for-granted definitions, axioms, and concepts". Human beings (and therefore scientists) are generally afraid of the unknown (Tart, 1972), even though the task of science comprises the exploration of novel and uncharted territory. The history of science clearly shows how difficult it is to revise deeply engrained theories. The scientific mainstream community once believed in phrenology, preformationism, telegony, phlogiston theory, luminiferous aether, contact electrification, the geocentric universe, the flat earth theory, etc. pp, the *errata* is long... All these obsolete theories have been superseded by novel scientific facts. The open question is: Which taken-for-granted theory is up for revision next? Unfortunately, scientific training leads to cognitive rigidity[4], as opposed to cognitive flexibility which is needed for creative ideation (ideoplasticity) and perspectival pluralism (Giere, 2006). From a neuroscientific point of view, a possible explanation for this effect is based on a

[4] Cognitive inflexibility has been investigated in obsessive-compulsive disorder and it has been correlated with significantly decreased activation of the prefrontal cortices, specifically the dorsal frontal-striatal regions (Britton et al., 2010; Gruner & Pittenger, 2017; Gu et al., 2008; Remijnse et al., 2013).

Hebbian neural consolidation account. That is, repeatedly utilised neural circuits are strengthened (Hebb, 1949) and become dominant and rigid, e.g., via the neuronal process of synaptic long-term potentiation[5] (Lomo, 2003). Interestingly, complex system theory suggests a bipolar (orthogonal) continuum ranging from rigidity on one end to chaos on the other. Integration lies interjacent between the extremes. Given that the cognitive system can be regarded as a complex system, this generic account might lend itself to conceptualise a "cognitive continuum of information processing states" (Faust & Kenett, 2014) ranging from rigid cognition to chaotic cognition. In a rigid neural network, nodes are only sparsely interconnected[6] (i.e., cognitive hyper-rigidity). In a chaotic neural network topology, on the other hand, virtually all nodes are interconnected (i.e., cognitive over-flexibility/chaos). In this schema, cognitive integration (viz., the linkage of differentiated parts (Siegel, 2010)) is consequently characterised by an intermediate neuronal network connectivity pattern which balances and synchronizes the polar extremes (i.e., adaptive/dynamic cognitive coherence). From a psychological point of view, scientist generally have great difficulties to revise their (oftentimes implicit) theories and adjust their associated "degrees of belief"[7] in the light of new evidence (a desirable quasi-Bayesian epistemological approach), particularly when they have vested personal/ideological interests in the predominant

[5] Using human cerebral organoids and *in silico* analysis it has been demonstrated that 5-MeO-DMT has modulatory effects on proteins associated with the formation of dendritic spines and neurite outgrowth (Dakic et al., 2017) which may influence neuroplasticity and hence ideoplasticity. 5-MeO-DMT has been found to match the σ_1 receptor. Because σ_1R agonism regulates dendritic spine morphology and neurite outgrowth it affects neuroplasticity which form the neural substrate for unconstrained cognition.
[6] Network interconnectivity is often quantitatively specified by the rich-club coefficient Φ. This networks metric quantifies the degree to which well-connected nodes (beyond a certain richness metric) also connect to each other. Hence, the rich-club coefficient can be regarded as a notation which quantifies a certain type of associativity.
[7] The Quinan "Web of Beliefs" (Quine & Ullian, 1978) provides an applicable semantic analogy to (Bayesian) neural network connectivity and the process of "belief updating" (i.e., modification of weights between neuron nodes).

status quo.[8] This resistance towards new theories, change, and innovation (i.e., exnovation) is deeply rooted in various (primarily unconscious) psychological processes which we will address later in more detail in the context of empirical findings which are incompatible with the predominant mainstream paradigm in science (viz., reductionistic materialism/physicalism/local realism) which has now been conclusively falsified by recent empirical findings from experimental quantum physics (but see Gröblacher et al., 2007; Hensen et al., 2015; Wiseman, 2015) — a milestone in the history of science. Various dispositional factors play a role in this context. Dispositional factors may be biological (e.g., genetic/epigenetic factors, specific receptor polymorphisms, dissimilarities in neurotransmitter concentrations,[9] neuroanatomical idiosyncrasies, variations in enteric microbiota composition/dysbiosis, etc.) and/or psychological in nature (e.g., personality traits, individual differences in cognitive abilities, childhood conditioning, cultural disparities, etc.). For instance, the psychological trait "closedmindedness" (Kruglanski, 2014) appears to be relevant in this regard. Closedmindedness is characterised as a general unreceptivity towards new ideas, arguments, and empirical findings. It is anticorrelated with the personality trait "openness to experience" which forms a major dimension in the widely applied five

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[8] This ego-driven *modus operandi* is unfortunately reinforced by an academic "climate of perverse incentives and hypercompetition" (Edwards & Roy, 2017) which does not foster sincere/genuine scientific authenticity and integrity and is antagonistic towards altruistic behaviour (a selfless attitude is a vital characteristic of an unbiased scientific ethos which transcends primitive personal interests). The pressure to "publish or perish" (Fanelli, 2012; Rawat & Meena, 2014) leads to "publication-bias" (Franco et al., 2014; J. D. Scargle, 2000) and promotes career-oriented behaviour which has been diagnosed as "pathological publishing" (Buela-Casal, 2014). Moreover, the quantitative (putatively "objective") evaluation of researchers based on bibliometric indices is causally related to an extrinsically motivated "impact factor style of thinking" (Fernández-Ríos & Rodríguez-Díaz, 2014) which is common among researchers and compromised scientific values. These nontrivial systemic issues seriously impede the scientific endeavour and have to be rectified for self-evident reasons. We are firmly convinced that instead of "playing the game" serious scientific researchers have an obligation to try their best "to change the rules" as it has recently been argued in an excellent AIMS NEUROSCIENCE article (C. D. Chambers et al., 2014). The ideals of science are fundamentally based on the quest for knowledge and truth and not on egoic motives such as career aspirations, social status, and monetary rewards (Sassower, 2015).

[9] See Appendix A3 for more details on the role of neurochemistry in the context of creativity and "unconstrained cognition".

factor model (FFM) of personality (McCrae, 1987). Openness[10] to experience (OTE) is a rather complex psychological construct which is broadly related to interindividual differences in information processing (Green-Hennessy & Reis, 1998), creative cognition and behaviour (George & Zhou, 2001), aesthetic perception (McCrae, 2007), absorption (Roche & McConkey, 1990), and cognitive style (Sadler-Smith, 2001), *inter alia*. For example, higher OTE scores are related to novelty seeking, curiosity, and intellectual achievement (Paunonen & Ashton, 2001). Moreover, OTE[11] is statistically significantly correlated with fluid intelligence (Cattell, 1963), divergent thinking,[12] and various facets of creativity (Silvia, Nusbaum, Berg, Martin, & O'Connor, 2009), to mention just the most salient aspects of this multidimensional personality construct. Hence, OTE is pivotal for the advancement of science into novel and unexplored territory, for memetic evolution, and consequently, *in sensu lato,* for the evolution of humanity as a species on this planet. Other important correlated psychological concepts which are related to openness and a nondogmatic scientific attitude are intellectual humility (Gregg, Mahadevan, & Sedikides, 2017; Krumrei-Mancuso & Rouse, 2016), epistemic curiosity (Eigenberger, Critchley, & Sealander, 2007; Litman & Spielberger,

[10] From a cognitive linguistic point of view, the usage of the concept "open" is interesting because it indicative of a spatial metaphor (Lakoff, 1993, 2014; Lakoff & Nuñez, 2000). The psychological concepts "**open**ness to experience" and "**closed**mindedness" are both based on primary conceptual metaphors (i.e., the spatial topology of containment (Lakoff & Johnson, 1980)). In other terms, the associated image metaphor implies that the cognitive system tends to be open or closed to novel information (viz., the diametrical psychological concepts can be represented as a gradual bipolar continuum: openness ↔ closedness).

[11] Recent neuropsychopharmacological work empirically demonstrated that the partial serotonin (5-hydroxytryptamin) agonist Psilocybin (O-phosphoryl-4-hydroxy-N,N-dimethyltryptamine) (Hofmann et al., 1958, 1959) enhances the personality trait openness to experience longitudinally (MacLean et al., 2011).

[12] Interestingly, it has been experimentally shown that psychotropic serotonergic compounds can enhance divergent thinking while decreasing conventional convergent thinking (Kuypers et al., 2016), an empirical finding of great importance which deserves much more detailed investigation. Moreover, it has been noted that "plasticity and open-mindedness" are primarily 5-HT_{2A} receptor mediated (as opposed to 5-HT_{1A}) and that "*a key function of brain serotonin transmission is to engage in processes necessary for change, when change is necessary*" (Carhart-Harris & Nutt, 2017, p. 1098). Moreover, cognitive flexibility appears to be positively modulated by 5-HT_{2A} agonists (Boulougouris, Glennon, & Robbins, 2008; Matias, Lottem, Dugué, & Mainen, 2017), thereby leading to enhancements in creative thinking (Frecska, Móré, Vargha, & Luna, 2012).

2003), and rational intelligence (i.e., critical thinking) (K. Stanovich, 2014). Moreover, group conformity and obedience to authority are important psychological constructs in this context. To use Richard Feynman's wise words which explicitly emphasise the importance of a lack of respect for authority figures:

"*Science alone of all the subjects contains within itself the lesson of the danger of belief in the infallibility of the greatest teachers in the preceding generation. […] Learn from science that you must doubt the experts. As a matter of fact, I can also define science another way: Science is the belief in the ignorance of experts.*" (Feynman, 1968)

The present thesis focuses on a novel emerging field within the cognitive science which is referred to as "quantum cognition" (Aerts, 2009; Aerts & Sassoli de Bianchi, 2015; Łukasik, 2018; Moreira & Wichert, 2016a; Z. Wang, Busemeyer, Atmanspacher, & Pothos, 2013). Quantum cognition can be broadly defined as a combination of quantum physics and cognitive psychology.[13] Recent empirical findings from quantum cognition deeply challenge the prevailing academic *modus operandi* adopted by many experts in cognitive psychology and the neurosciences. The counterintuitive theoretical and epistemological implications of quantum physics require a great deal of OTE (particularly divergent thinking), intellectual humility (as opposed to intellectual arrogance), and epistemic curiosity (Echenique-Robba, 2013), because they challenge some of our most fundamental beliefs about the nature of reality, specifically the widely

[13] It should be emphasised at the outset that quantum cognition is independent from the Orch-OR quantum brain hypothesis (Hameroff & Penrose, 2014b) which postulates that quantum processes within the neuronal cytoskeleton (i.e., dendritic-somatic microtubules) form the basis for consciousness. Orch-OR is an acronym for "orchestrated objective reduction" which has been popularised by Sir Roger Penrose and Stuart Hameroff. We refer to Appendix A2for a brief synopsis of this integrative theory which combines findings from neuroscience, molecular biology, quantum physics, pharmacology, quantum information theory, and philosophy.

held notion of "local realism"[14] (Giustina et al., 2015; Hensen et al., 2015; Wiseman, 2015). *Prima vista*, many empirical findings from quantum physics seem irrational/paradoxical, highly counterintuitive, and incompatible with our most fundamental beliefs about reality. Consequently, they cause a significant amount of "cognitive dissonance" (i.e., mental discomfort/psychological stress due to contradictory beliefs) (Festinger, 1957). Therefore, it is predictable that these inconvenient empirical facts are ignored in order to circumvent psychological tensions.[15] To appreciate the novel findings the deeply engrained "need for closure" (Webster & Kruglanski, 1994) needs to be actively counteracted[16] in order to process these novel seemingly irrational/paradoxical empirical facts in a less biased/prejudiced manner. In other words, human beings generally strive for consistency and conflicting information is likely to be disregarded. As William James pointed out, it is easy to

[14] Local realism is the widely held belief that "the world is made up of real stuff, existing in space and changing only through local interaction", as Wiseman formulates it in a NATURE article entitled "Quantum physics: Death by experiment for local realism" (Wiseman, 2015, p. 649). The widely held belief in the veracity of this local-realism hypothesis has now been conclusively falsified., i.e., empirical findings "rigorously reject local realism". We urge the sceptical reader to verify this claim. The scientific ramification of this cutting-edge evidence-based paradigm shift are extremely far-reaching and require a substantial degree of open-mindedness, cognitive flexibility, and epistemological humility.

[15] However, given that these inconvenient findings can be applied and economically exploited in the real-world (e.g., quantum computation/communication/encryption/teleportation etc. pp.) it is no longer feasible to just ignore them or dismiss them derogatively as "purely philosophical". For instance, the understanding and application of quantum principles like non-locality can be a decisive factor in cyber-war and physical war (cf. Alan Touring and the enigma code (Hodges, 1995)). Google and NASA are currently heavily investing in the technological application of quantum principles which were previously thought to be "merely" of philosophical/theoretical relevance (e.g., quantum AI (Sgarbas, 2007; Ying, 2010)).

[16] The default-interventionist account of thinking and reasoning (Evans, 2007) appears to be relevant in this context. The need for closure is arguably an automatic and mainly unconscious process which needs to be actively antagonised by more systematic higher-order cognitive processes which rely on executive (prefrontal) cortical functions (Figner et al., 2010; Hare, Camerer, & Rangel, 2009). From a cognitive economics perspective (Chater, 2015), these interventions upon frugal heuristic processes are costly in energetic terms and therefore only used parsimoniously. Moreover, it should be noted that rational intelligence is relatively independent from general intelligence, i.e., IQ ≠ RQ. As former APA president Robert Sternberg formulated it "… IQ and rational thinking are two different constructs … The use of the term 'rational intelligence' is virtually identical with the usual definition of critical thinking." (Sternberg, 2018, p. 185). In other words, otherwise intelligent people frequently make irrational decisions and draw logically invalid conclusions and are therefore perhaps not as smart as they are considered to be. Stanovich labels the lack of rationality "disrationalia" in order to describe the inability to "think and behave rationally despite adequate intelligence" (K. Stanovich, 2014, p. 18). We compiled additional information and an RQ test under the following URL: http://irrational-decisions.com/?page_id=2448

prima facie reject ideas which are not readily "classifiable" in the prevailing scientific framework. However, lateral and divergent "nonconformist" rational thinking is a much harder task.[17] Immanuel Kant's timeless advice which he formulated in his classic essay "Was ist Aufklärung?" (What is enlightenment?) still reverberates with us today:
Sapere aude! (Kant, 1804)

1.1 Psychology: A Newtonian science of mind

Lateral thinkers interested in the mind have been inspired by the methods and results of physics for a long time. For example, the British empiricist philosopher John Locke (*1632; †1704) was imbued with the corpuscular theory of light (primarily formulated by his friend Sir Isaac Newton) when he formulated his "corpuscular theory of ideas" in his profoundly influential publication "An essay concerning human understanding" which appeared in 1690. Locke transferred and generalised the axioms of Newtons physical theory (which concerned the lawful behaviour of matter) to the psychological (nonmaterial) domain. In other terms, Locke committed himself to a reductionist Newtonian science of the mind (Ducheyne, 2009). Corpuscularianism is an ontological theory which postulates that all matter is assembled of infinitesimally small particles (Jacovides, 2002). This notion is similar to the theory of atomism, except that, in contrast to atoms (from the Greek *átomos*, "that which is indivisible")[18], corpuscles can

[17] At this place, a cautionary note should be cited: It has been convincingly argued that in the current academic climate, critical "sincerely scientific" thinking is a dangerous activity which is associated with various serious social risks which can have far-reaching consequences for the scientifically-minded cogniser (Edwards & Roy, 2017). Divergent thinking can lead to ostracisms and various other detrimental consequences, especially when central (oftentimes implicit) in-group norms are challenged, e.g., reductionist materialism/local realism. The extensive social psychology literature (e.g., group dynamics, groupthink, conformity, consensus/dissent) is conclusive on this point (Bastian & Haslam, 2010; Postmes, Spears, & Cihangir, 2001; K. D. Williams, 2007).
[18] The idea behind the atom is that matter is composed of primordial material elements which are fundamental to all of existence. Etymologically, the Greek term *átomos* (ἄτομος) is a composite lexeme composed of the negating prefix *á*, meaning "not" and the word stem *tomṓteros*, "to cut". Ergo, its literal

theoretically be further subdivided (*ad infinitum*). According to Newton, these corpuscles are held together by a unifying force which he termed "gravitation" (Rosenfeld, 1965). One of Locke's primary concerns in this regard was: What are the most elementary "particles" of human understanding (i.e., what are the "atoms of thought"), where do they come from, and how are they held together? Locke rejected the Cartesian notion of innate (God-given) ideas, but he accepted some intuitive principles of the mind (e.g., the law of contradiction) which he assumed must be in place *a priori* in order for any knowledge to arise.[19] In addition to this kind of intuitive knowledge about propositional logic, which he conceptualized as immediate, indubitably knowable and certainly true, Locke also accepted some forms of demonstrative knowledge to be certainly true. For example, the axioms of Euclidean geometry. In contrast to intuitive knowledge, one has to perform a series of mathematical proofs in order to reach a certain general conclusion which is true in all contexts and circumstances.[20] Having defined these principles he pursued his initial question: What are the most elementary "particles" of human cognition, where do they come from, and how are they held together? Locke's answer is simple: Ideas come from experience and are held together by associational forces (Halabi, 2005). That is, empirical knowledge which is accumulated diachronically during the course of a lifetime forms the basis of thought. Locke argues that the most elementary act is the sensory act and the most elementary contents of the mind are sensations. He remarks:

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meaning is "not cuttable". In the memetic history of human thought, the term atom is ascribed to the Greek philosophers Leucippus and Democritus (Pullman, 2001) even though similar atomistic concepts were present in ancient Indian schools of thought (Rasmussen, 2006).

[19]The Greek term "*Epistemonicon*" (i.e., the cognitive ability by which humans comprehend universal propositions) provides an apposite semantic descriptor for this psychological faculty.

[20] From a modern dual-systems perspective on cognitive processes, automatic (associative) and effortless intuition is a System 1 process, whereas sequential and effortful logical reasoning is a System 2 process (Kahneman, 2011) (but see Appendix A7). Hence, Locke's theory can be regarded as a predecessor of modern dual-process theories which are now ubiquitous in many fields of psychology and neuroscience (Jonathan St B.T. Evans, 2003; Jonathan St B.T. Evans & Stanovich, 2013; Thompson, 2012).

"*For to imprint anything on the mind without the mind's perceiving it, seems to me hardly intelligible*" (Chapter 2 - On innate ideas). In other words, what enters the mind comes through the sensorium and these elementary sensations must be connected somehow. According to Newton, the corpuscular components of reality are held together by gravitational forces, i.e., Newton's law of universal gravitation which follows the inverse-square law.[21] Locke ingeniously applied this idea to elementary sensations and proposes the principle of "association" as the mental counterpart to physical gravitation.[22] *Ex hypothesi*, objects or events which are frequently experienced together are connected by associative processes.[23] They thereby recombine to form simple ideas. Out of simple ideas, increasingly complex ideas are hierarchically assembled by the binding force of association – this the Lockean associative "logic of ideas" (Yolton, 1955). The Lockean associationist memetic[24] account is still viable today. e.g., associative (Bayesian) neural networks in artificial intelligence research.

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[21] The inverse-square law can be mathematically notated as follows: gravitational intensity $\propto \frac{1}{\text{distance}^2}$
In the context of Locke's psychological theory, the term "gravitational intensity" can be replaced with "associational intensity". While gravitation is the attraction of two physical objects, association describes the attraction between mental concepts (i.e., ideas). For instance, the "distance" between various concepts can be indirectly quantified by variations in reaction-times in a semantic priming paradigm, for instance, the implicit-association test (IAT) (Greenwald & Farnham, 2000; Sriram & Greenwald, 2009). The concepts "tree" and "roots" are closer associated (i.e., the "associational intensity" is stronger) than the concepts "university" and "beer" (perhaps this is an unfortunate example, but it illustrates the general point).

[22] Interestingly, it has been noted by historians of philosophy and science that "Locke's attitude towards the nature of ideas in the Essay is reminiscent of Boyle's diffident attitude towards the nature of matter" (Allen, 2010, p. 236).

[23] This Lockean idea can be regarded as the predecessor of Hebbian engrams and assembly theory – "cells that fire together wire together" (Hebb, 1949). The formulaic description of Hebb's postulate is as follows:

$$w_{ij} = \frac{1}{p}\sum_{k=1}^{p} x_i^k x_j^k,$$

[24] The science of memetics tries to (mathematically) understand the evolution of memes, analogous to the way genetics aims to understand the evolution of genes (Kendal & Laland, 2000). Locke's early contributions are pivotal for the development of this discipline which is embedded in the general framework of complex systems theory (Heylighen & Chielens, 2008). Memetics is of great importance for our understanding of creativity and the longitudinal evolution of ideas in general. Memes reproduce, recombine, mutate, compete and only the best adapted survive in a given fitness landscape. Similar to genotypes, the degree of similarity/diversity between memes (and their associated fitness values) determines the topology of the fitness landscape.

Locke was clearly far ahead of his time and the associative principles he formulated where later partly experimentally confirmed by his scientific successors, e.g., Ivan Pavlov (Mackintosh, 2003) and later by the behaviourists in the context of S-R associations (Skinner, Watson, Thorndike, Tolman, etc. pp.). Furthermore, the Newtonian/Lockean theory of how ideas are composed in the mind forms the basis of the "British Associationist School" with its numerous eminent members (David Hartley, Joseph Priestley, James Mill, John Stuart Mill, Alexander Bain, David Hume, *inter alia*). In England, the Associationist School asserted an unique influence on science and art alike and the principles of associationism and connectivism are still widely applied in many scientific fields, for instance, in the psychology of associative learning and memory (Rescorla, 1985) and in computer science (for instance, associative neural networks like cutting-edge deep/multi-layered convolutional neural nets (Kivelä et al., 2014; Lecun, Bengio, & Hinton, 2015)). To indicate Newton's and Locke's pervasive influence on psychology it could for instance be noted that Pavlov's classical and Skinner's operant conditioning can be classified as a form of associationism, as can Hebbian learning which is ubiquitously utilised in science.

Until today, psychology and much of science operates on the basis of a materialistic, mechanistic, and deterministic quasi-Newtonian paradigm.

1.2 Shifting paradigms: From Newtonian determinism to quantum indeterminism

The crucial point is that Locke's associationist (Newtonian) theory of mind is fundamentally deterministic (and consequently leaves no room for free will (cf. Conway & Kochen, 2011)). Newton's "*Philosophiæ Naturalis Principia Mathematica"* (Mathematical Principles of Natural Philosophy) originally published in 1687 is among the most influential works in the history of science and Newton's materialistic mechanistic determinism shaped and impacted scientific hypothesizing and theorising in multifarious ways. In 1814, Pierre Simon Laplace famously wrote in his formative "*Essai philosophique sur les probabilités*" (A Philosophical Essay on Probabilities):

"*We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.*" (Laplace, 1814, p. 4)[25]

This deterministic view on reality was extremely influential until the late 18th century and is still implicitly or explicitly the ideological *modus operandi* for the clear majority of scientists today. However, in physics, unexplainable (anomalous) data and inexplicable abnormalities kept accumulating (e.g.: the three-body-problem, the results of Young's double-slit experiment, etc.) and finally a non-deterministic (stochastic) quantum perspective on physical reality evolved as exemplified by the following concise quotation concerning the uncertainty principle by Werner Heisenberg from "*Über die Grundprinzipien der Quantenmechanik*" (About the principles of quantum mechanics):

[25] The full essay is available on the Internet Archive under the following UR: https://archive.org/details/essaiphilosophiq00lapluoft/page/n5

"In a stationary state of an atom its phase is in principle indeterminate," (Heisenberg, 1927, p. 177)[26]

One of the most eminent adversaries of this indeterministic theoretical approach, Albert Einstein, vehemently disagreed with the stochastic uncertainty inherent to quantum mechanics. For example, Einstein wrote in one of his letters to Max Born in 1944:

"We have become Antipodean in our scientific expectations. You believe in the God who plays dice, and I in complete law and order in a world which objectively exists, and which I, in a wildly speculative way, am trying to capture. I firmly believe, but I hope that someone will discover a more realistic way, or rather a more tangible basis than it has been my lot to find. Even the great initial success of the quantum theory does not make me believe in the fundamental dice-game, although I am well aware that our younger colleagues interpret this as a consequence of senility. No doubt the day will come when we will see whose instinctive attitude was the correct one." (Born, 1973, p.149)[27]

Einstein's general and special theory of relativity, radical though they were, explain natural phenomena in a Newtonian deterministic fashion, thereby leaving the established forms of reasoning, logic, and mathematics of the 19th century undisputed. By comparison, quantum theory completely changed the conceptual framework of science due to its fundamentally stochastic indeterminism. It has not just changed

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[26]The mathematical formulation of the Heisenbergian uncertainty principle is: $\Delta x \Delta p \geq \frac{1}{2}\hbar$,
where Δ signifies standard deviation (spread or uncertainty),
x and p signify the position and linear momentum of a given particle,
$\hbar$ signifies a specific fraction of Planck's constant (Planck's constant divided by 2π).
That is, an accurate measurement of position disturbs momentum and vice versa (see Robertson, 1929).
For a discussion of the "inextricable" relation between non-locality and the uncertainty principle see (Oppenheim & Wehner, 2010)

[27] The Einstein-Born letter are available on the Internet Archive under the following URL: https://archive.org/details/TheBornEinsteinLetters/

scientific concepts of physical reality but our understanding of the most essential rationality principles in general, i.e., a new form of quantum logic was developed (Beltrametti & Cassinelli, 1973). Quantum theory is now by a large margin the most reliable theory science has ever developed because its quantitative predictions are extremely accurate and have been tested in countless domains. Despite this unmatched track record, contemporary psychology, the neurosciences, and the biomedical sciences[28] (and their associated statistical methods) are still modelled *after* the antiquated and *de facto* outdated Newtonian/Lockean deterministic worldview and these scientific disciplines (and others) have not yet aligned themselves with the far-reaching implications derived from quantum theory. In other words, the revolutionary reformation of Newtonian mechanics has not yet reached psychology which is still based on the hypothetical premise of local realism of classical physics. In fact, it could be effectively argued that the classical probability framework (which is used in almost exclusively in all cognitive modelling efforts) exhibits the defining characteristics of a tenacious Kuhnian paradigm. As Thomas Kuhn articulates in his influential book "The structure of scientific revolutions":

"... 'normal science' means research firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice. Today such achievements are recounted, though seldom in their original form, by science textbooks, elementary and advanced. These textbooks expound the body of accepted theory, illustrate many or

[28] It has been argued that the entire scientific endeavour has not yet come to terms with the radical revolution which has been set in motion by quantum physics (Dowling & Milburn, 2003; Heisenberg, 1958). Science wants to define itself as objective, detached, and neutral. Several findings from quantum physics challenge this identity. For instance, the observer effect questions the possibility of objective measurements and the violations of Bell inequalities challenge the notion of local realism which forms the basis of much of scientific theorising (Gröblacher et al., 2007).

all of its successful applications, and compare these applications with exemplary observations and experiments. Before such books became popular early in the nineteenth century (and until even more recently in the newly matured sciences), many of the famous classics of science fulfilled a similar function. Aristotle's Physica, Ptolemy's Almagest, Newton's Principia and Opticks, Franklin's Electricity, Lavoisier's Chemistry, and Lyell's Geology—these and many other works served for a time implicitly to define the legitimate problems and methods of a research field for succeeding generations of practitioners." (T. S. Kuhn, 1962, p. 10)

1.3 Quantum cognition: An emerging novel paradigm in psychology

Psychology as a scientific discipline has primarily modelled its methods *after* the highly successful achievements of classical physics, thereby longing for the acceptance as a "hard" empirical science (this has been termed "physics envy" (Fish, 2000)). Hence, it is not surprising that psychology almost always lags with regards to the evolution of mathematical, methodological, and conceptual principles. Moreover, it follows that physicists (who are generally aware of the paradigm shifts within their field) will be among the first to accept a high degree of uncertainty and indeterminism in the methods of psychology (e.g., Busemeyer, Pothos, Franco, & Trueblood, 2011b; Z. Wang et al., 2013).

After John Locke's quasi-Newtonian insights, the time is ripe that scholars of the mind take a fresh look at the empirical findings physics provides in order to adapt their epistemology and research methods. Especially quantum probability theory (herein after referred to as QP theory) has very promising potential for the enrichment (and deep revision) of many concepts that are widely and mainly unreflectively utilised in

psychology (and various other branches of science). Based on anecdotal data, we are inclined to believe that the vast majority of psychologists and neuroscientists are utterly unaware of the breakthroughs in quantum physics (let alone their ontological and epistemological implications). This is presumably due to a lack of interdisciplinary discourse (Lélé & Norgaard, 2005). Furthermore, QP theory has not yet been included in any mainstream statistical textbook (let alone its integration into academic curricula). However, the transdisciplinary ramifications of quantum physics are extremely far reaching as Niels Bohr pointed out more than half a century ago:
"In atomic science, so far removed from ordinary experience, we have received a lesson which points far beyond the domain of physics." (Bohr, 1955, p. 171)

1.4 Observer-effects, noncommutativity, and uncertainty in psychology

Based on accumulating converging empirical evidence (e.g., Aerts, Broekaert, & Gabora, 2011; beim Graben, 2013; Moreira & Wichert, 2014; Z. Wang et al., 2013), it seems plausible that measurements can affect not only physical processes (an empirical fact that has been firmly established in quantum physics (e.g., Alsing & Fuentes, 2012; Bell, 2004; Rosenblum & Kuttner, 2002)) but also cognitive and behavioural processes. For example, the widely debated "unreliability" of introspection (Engelbert & Carruthers, 2010), including all self-report measures (e.g., questionnaire studies), might be partially due to interference effects caused by self-observation. That is, the mere act of introspection (an internal self-measurement) interferes with the state of the cognitive system to be evaluated, thereby confounding the introspective measurement outcome. To be more explicit, introspection might distort the internal state in question because this kind of self-observation focuses mental energy on the process in question (analogous to a laser device focusing physical energy on a particle)[29] which causes the state concerned to undergo a transformation, possibly via collapse of the "mental wave-function" (A. Khrennikov, 2003, 2009, 2010). Moreover, the introspective process may be influenced by idiosyncratic motives and intentions which makes the self-measurement outcome even more unreliable due to a more systematically biased distortion of the measurement of the psychological observable.

Apart from the observer-effect, the uncertainty-principle appears to be relevant to cognitive processes, too (Busemeyer & Bruza, 2012). Uncertainty is ubiquitous in multifarious decision-making scenarios (Kahneman & Tversky, 1974) and it has been noted that "QP theory is potentially relevant in any behavioural situation that involves uncertainty" (Pothos & Busemeyer, 2013, p.255). Moreover, QP has the potential to parsimoniously account for empirical findings which appear paradoxical and irrational in the classical probability framework (Z. Wang et al., 2013). Nobel Prize laureate Daniel Kahneman, editor and co-author of the widely studied book "Judgement Under Uncertainty: Heuristics and Biases" (*inter alia*), is momentarily presumably the most eminent researcher in the field of reasoning and decision making. Therefore, his work is the optimal starting point for an application of QP principles (but see Pothos and Busemeyer, 2013). Kahneman can be categorized as a dual-process theorist (Jonathan St B.T. Evans, 2003; Frankish, 2010). (The basic nexus of dual-process theories of cognition is adumbrated in Appendix A7 and we recommend to the unfamiliar reader to consult the addendum before continuing because a basic understanding of the dual-process theory is required in order to appreciate the following argumentation.)

During his Nobel Prize lecture, Kahneman introduced his research agenda as an

[29] A similar idea inspired by quantum physics has recently been published in a different context in a paper published in the Philosophical Transactions of the Royal Society: "Social Laser: Action Amplification by Stimulated Emission of Social Energy" (A. Khrennikov, 2015).

“attempt to map departures from rational models and the mechanisms that explain them”. Moreover, he formulated that one of the overarching features of his research projects is to “introduce a general hypothesis about intuitive thinking, which accounts for many systematic biases that have been observed in human beliefs and decisions” (Kahneman, 2002). He advocates an evolutionary perspective on reasoning and his reflections are based on the assumption that there is a kind of quasi biogenetic progression in the evolution of cognitive processes starting from automatic processes which form the fundamental basis for the evolution of more deliberate modes of information processing. The postulated diachronic phylogenetic history of cognitive processes can be adumbrated as follows:

PERCEPTION → INTUITION → REASONING

According to this sequential view on the Darwinian evolution of cognitive systems, perception appears early on the time-line of history, whereas reasoning evolved relatively recently. Intuition is intermediate between the automatic (System 1) processes of perception and the deliberate, higher-order reasoning (System 2) processes that are the hallmark of human intelligence (Kahneman, 2003). Furthermore, Kahneman proposes that intuition is in many ways similar to perception and the analogy between perception and intuition is the common denominator of much of his distinguished work.

Thus far, QP principles have primarily been tested in higher-order cognitive processes, for instance, in political judgments and affective evaluations (e.g., Z. Wang & Busemeyer, 2013; White, Barqué-Duran, & Pothos, 2015; White, Pothos, & Busemeyer, 2014b). Following Kahneman’s line of thought, one could ask the question: Do the principles of QP also apply to more basic perceptual processes which evolved much earlier in the phylogenetic evolutionary tree? That is, do the principles of quantum cognition (for instance, the crucial noncommutativity axiom) also apply to the most fundamental perceptual processes like visual perception? If so, this would provide supporting evidence for the generalisability of QP principles. In addition, this kind of evidence would have the potential to cross-validate recent findings concerning affective (emotional) evaluations and attitudinal judgments (White et al., 2015, 2014b). However, hitherto the literature on QP focuses primarily on judgments and decisions in higher-order (System 2) cognitive processes[30]. Our experiments aim to bridge this empirical gap. In this thesis, we report experimental evidence that extends this line of work into the domain of basic perceptual (System 1) processes. We designed several experiments in order to test various predictions derived from the QP model. Specifically, we employed a reductionist psychophysics approach in order to address the question whether QP principles are applicable to low-level perceptual processes. We argue, that evidence which support the applicability of QP principles to perceptual processes would cross-validate and corroborate the findings made in the domain of higher-order cognitive processes (emotions, judgements, reasoning). The novelty of our approach is thus to introduce principles from quantum probability to psychophysics. In the following section, we will discuss why the marriage between psychophysics and quantum cognition is fruitful.

[30] There are some exceptions: For instance, the ingenious work by Atmanspacher et al. applied various quantum principles (e.g., temporal nonlocality, superposition/complementarity, the quantum Zeno-effect) to the perception of bistable ambiguous stimuli (Atmanspacher & Filk, 2010, 2013, Atmanspacher et al., 2004, 2009). We will discuss these insightful findings in subsequent sections.

1.5 Psychophysics: The interface between Psyche and Physis

In order to understand the relationship between psychophysics and quantum cognition it is necessary to review the development of the discipline because the mainstream accounts given in most textbooks on psychophysics is misleading and highly selective (Boring, 1928, 1961; Scheerer, 1987), partly due to the fact that Fechner's voluminous work has only been partially translated from German into English. In the following section, we will provide a brief account of the history of psychophysics with an emphasis on Gustav Fechner's formative contributions (Fechner has been regarded as "inadvertent founder of psychophysics" (Boring, 1961)).

Contemporary psychology (the "nasty little subject" as William James labelled it) is an amalgamation of science and philosophy. The scientific aspect of psychology is based on the quantitative experimental scientific tradition and its focus on prediction, experimental verification, and precision of measurement. The philosophical aspect of psychology (which is complementary to the scientific aspect) is based on empiricisms and its emphasis on observation as a means to acquire knowledge. Historically, precise quantitative measurements became of great importance in the beginning of the 18th century and this development towards quantitative precision was primarily based on pragmatic considerations. The ability to successfully navigate the oceans was of great importance in this time period (not least for financial/economic reasons) and tools and instruments were developed in order to enable accurate marine navigation. At the same time, astronomy significantly gained in status due to Newtons and Kepplers theorizing. Precise measurement instruments were required to empirically verify the novel scientific theories. Especially in Great Britain (Wolfschmidt, 2009), for instance in Greenwich (Howse, 1986), astronomical observatories were built. These observational facilities systematically compared their findings in order to reach inter-observer consensus, thereby increasing the accuracy and robustness of observations. At the same time, the human sensory organs became a matter of great scientific interest, the reason being that astronomy relied on the human observer (percipient) and on the precision of the sensorium. Idiosyncratic observational differences could multiply and have large-scale ramifications for the observational models which were formulated in this period. Based on the philosophical school of empiricism, observational scientists developed a keen interest in the optimal/ideal observer and the perceptual processes which undergird signal detection. That is, a precise understanding of the perceptual system played a pivotal role for very practical reasons. The key question was, how good are human percipients in judging minute differences in the external world (for instance, the brightness of visual stimuli, e.g., faint stars)[31]. That is, perceptual decision-making became a topic of great interest because it had real-world implications and infinitesimal perceptual deviations could incrementally amplify and have large scale real-world implications. On the other hand, there was a philosophical interest in perception due to the empiricist stance that the mind is a *tabula rasa* which is “furnished by experience” (Locke, 1796), in accordance with the Peripatetic axiom: "*Nihil est in intellectu quod non prius fuerit in sensu*" (nothing is in the intellect that was not first in the senses (but see Kuksewicz, 1982)). According to the Aristotelian notion of the "*intellectus agens*” (active intellect) abstract universal meaning is inductively derivable from particular empirical (sensory/perceptual) data. Consequently, how exactly the contents of the mind are furnished by sensory inputs became a topic of great philosophical and psychological importance (according to this perspective, incoming sensory data determines the

[31] It has indeed been argued that Fechner’s law was anteceded by astronomers who investigated stellar magnitudes, but that these early “astro-psychophysicists” are ignored in the historical discourse on psychology (Pliskoff, 1977)

contents of the mind which was regarded as a "blank slate" which is imprinted by sense data). From a purely pragmatic point of view, discriminatory acuity and the exact quantification of perceptual measurement errors became subjects of particular interest because they had far-reaching consequences in the real-world, for instance, navigation on the sea relied on precise and accurate descriptions of various properties of the external world. The refinement of exact measurement instruments was another closely related research topic of utmost practical importance, primarily for political and economic reasons (i.e., colonialism). Taken together, these historical developments could be regarded as primary impetus for the development of western psychophysics. However, it were German scientists in the beginning of the 19th century who started psychophysics as a systematic experimental academic discipline. Particularly, Ernst Heinrich Weber (1795 - 1878) who was a professor at the University of Leipzig (now considered as one of the founding fathers of modern experimental psychology) started a research program which focused meticulously on the precision of the human senses. One of the textbook examples is Weber's investigation of how accurate percpients are at differentiating the intensity of two stimuli, for instance, between the brightness of two lights. That is, what is the least perceptible difference[32] a human observer can detect between two visual stimuli which differ only slightly in their brightness. In a prototypical psychophysics experiment the subject would be presented with two lights with varying brightness levels. One would be the standard light (modulus) and the other the comparison light. Weber would then quantitatively determine at which point the subject could detect a difference in brightness between the standard and the comparison stimulus. On the basis of his experimental findings, he formulated the following law

[32] The now widely used psychophysical concept is often acronymized as JND, i.e., just noticeable difference (Gescheider, 1997).

known as Weber's law or Weber's ratio: The ratio of the value of difference between the standard and the comparison stimulus ΔR divided by the value of the standard stimulus R would produce a mathematical constant k. Weber's law has been systematically studied in many sensory modalities (e.g., audition, olfaction, gustation, etc.). Weber published his findings in the 1830s. The main conclusion of his empirical investigations was that perception can be quantified in a mathematical fashion and that there is a systematic lawful relationship between the physical world and the mental world of perception which can be precisely axiomatized.

Equation 1. Weber's law.

$$k = \frac{\Delta R}{R}$$

Approximately 30 years later (at the same university in Leipzig) a physicist by the name of Karl Gustav Fechner observed the sun to study visual negative afterimages. To his great dismay he lost his eyesight due to photokeratitis (blindness caused by exposure of insufficiently protection of the eyes from ultraviolet light). He already was a very successful physicist and he received a professorial chair in his early 30s for his work on electricity (one of the youngest professors of his time in Germany). However, his blindness prevented him from pursuing his academic profession and ophthalmologists predicted that his eyesight would not return. Fechner became seriously depressed and lived a very melancholic life. Because he was unable to read, he spent most of his time in contemplation in a dark room and began to become almost obsessively concerned with the relationship between mind and matter.

However, after several months of "introspection" his ophthalmic condition reversed. At this fortunate turning point in his life, he decided to dedicate his intellect to a new endeavour. Inspired by his profound experiences, Fechner set out to prove that the same divine force which is responsible for the creation of the external physical world is also responsible for the creation of the internal psychological world. Fechner intended to show that there is a set of connecting principles which connects the psychological realm with the physical realm. That is, he intended to create a novel science which focuses on the relationship between the psychological and the physically domain. He termed this new scientific discipline "psychophysics". Today psychophysics is a very well-developed discipline within the arena of psychology and it can be said without any doubt that it is the most quantitative and precise of all psychological schools of thought. Modern psychophysics is in a position to produce highly reliable data with regards to physical stimuli and the sensations and perceptions they produce in the percipient. To be more exact, Bruce, Green, and Georgeson (1996) define psychophysics as "*the analysis of perceptual processes by studying the effect on a subject's experience or behaviour by systematically varying the properties of a stimulus along one or more physical dimensions*."

According to historians of science, a solution to the problem of the relationship between psyche and physis came to Fechner one morning in October 1850 in a sudden epiphany (Meischner-Metge, 2010). This particular day is still yearly celebrated as "Fechner's day" which has even beenofficially celebrated in Asia (Mori, 2008). Fechner thought: If he would be able to empirically establish quantitative relations between particular physical stimuli and the accompanying sensation he would be able to proof the unity (i.e., nonduality) of mind and matter (cf. Boring, 1928). In his meticulous experiments, Fechner analysed countless judgments from his experimental subjects and he logarithmically extended Weber's law and developed what is now known as Fechner's law (Laming, 2011; Norwich & Wong, 1997)[33]:

Equation 2. Fechner's law.

$$p = k\ln\frac{S}{S_0}$$

where k signifies a perceptual modality specific constant.

Fechner was keenly aware of the far-reaching implications of his idea, namely that an element of human consciousness could be systematically quantified in mathematical terms. Hence, Fechner played a pivotal role in the emergence of modern experimental psychology and his achievements were later explicitly recognised by Wilhelm Wundt. Fechner's research methodology is widely emulated in countless psychology laboratories until today. Contrary to mainstream belief, Fechner was antagonistic towards materialism and the associated mechanistic paradigm which prevailed during his lifetime until today (Scheerer, 1987). He rejected dualistic notions and became convinced of the existence of a unitary reality which forms the foundation of the material and the psychological reality (an ontological theory named "dual-aspect monism" (Atmanspacher, 2012)). However, this fact is mainly neglected in the psychophysics literature which focuses exclusively on his quantitative work and neglects his deep philosophical motivation which provided the impetus for his theorising, a well-known bias in the history of science which overemphasises the nomological "context of justification" and neglects the idiosyncratic "context of discovery" (Bowers, Regehr, Balthazard, & Parker, 1990). Fechner's nondual

[33] It should be noted that historians of science trace the antecedents of Fechner's law to several British astronomers, *inter alia*, the polymath Sir John Herschel. It has been argued that those early psychophysicists have not been given their due (Pliskoff, 1977).

perspective on mind and matter is compatible with the monistic theory of Baruch de Spinoza[34], viz., dual-aspect monism (Charlton, 1981; Daniels, 1976; Della Rocca, 2002). A similar nondual conception was later discussed between the depth-psychologist Karl Gustav Jung and quantum physicist and Nobel laureate Wolfgang Pauli, i.e., the "Pauli-Jung conjecture" (but see Atmanspacher, 2012)[35]. The British quantum physicist David Bohm describes the mind-matter (psycho-physics) dichotomy in terms of an ontological dimension he terms "implicit and explicit order". The implicit

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[34] Albert Einstein was deeply influenced by Spinoza's thoughts. In 1929, Einstein wrote (originally in German): "*I believe in Spinoza's God, who reveals himself in the harmony of all that exists, not in a God who concerns himself with the fate and the doings of mankind*." Moreover, he stated in the Japanese magazine "Kaizō" in 1923: "*Scientific research can reduce superstition by encouraging people to think and view things in terms of cause and effect. Certain it is that a conviction, akin to religious feeling, of the rationality and intelligibility of the world lies behind all scientific work of a higher order. [...] This firm belief, a belief bound up with a deep feeling, in a superior mind that reveals itself in the world of experience, represents my conception of God. In common parlance this may be described as pantheistic*". In a letter to a young girl named Phyllis he wrote in 1936 *"... everyone who is seriously involved in the pursuit of science becomes convinced that some spirit is manifest in the laws of the universe, one that is vastly superior to that of man. In this way the pursuit of science leads to a religious feeling of a special sort, which is surely quite different from the religiosity of someone more naive*." (Einstein & Alice Calaprice (ed.), 2011)

[35] This interdisciplinary discussion can be regarded as a first attempt to integrate quantum physics and psychology into a unified theoretical "psychophysical" framework. We are convinced that many topics which were addressed in the voluminous correspondence between Jung and Pauli will become of great importance for future psychophysical theories which focus on the interplay between "mind and matter" (note that dualistic terminology cannot be avoided). For instance, a fascinating topic Jung and Pauli discussed in this context was the acausal connecting principle termed "synchronicity" (Donati, 2004; C.G. Jung, 1975; Main, 2014). In his eponymous book Jung gives the following prototypical example of a synchronistic event:

"My example concerns a young woman patient who, in spite of efforts made on both sides, proved to be psychologically inaccessible. The difficulty lay in the fact that she always knew better about everything. Her excellent education had provided her with a weapon ideally suited to this purpose, namely a highly polished Cartesian rationalism with an impeccably "geometrical" idea of reality. After several fruitless attempts to sweeten her rationalism with a somewhat more human understanding, I had to confine myself to the hope that something unexpected and irrational would turn up, something that would burst the intellectual retort into which she had sealed herself. Well, I was sitting opposite her one day, with my back to the window, listening to her flow of rhetoric. She had an impressive dream the night before, in which someone had given her a golden scarab — a costly piece of jewellery. While she was still telling me this dream, I heard something behind me gently tapping on the window. I turned round and saw that it was a fairly large flying insect that was knocking against the window-pane from outside in the obvious effort to get into the dark room. This seemed to me very strange. I opened the window immediately and caught the insect in the air as it flew in. It was a scarabaeid beetle, or common rose-chafer (Cetonia aurata), whose gold-green colour most nearly resembles that of a golden scarab. I handed the beetle to my patient with the words, 'Here is your scarab.' This experience punctured the desired hole in her rationalism and broke the ice of her intellectual resistance. The treatment could now be continued with satisfactory results." (C.G. Jung, 1975)

order is in principle epistemologically accessible whereas the implicit order is purely ontological and epistemologically inaccessible:

"*At each level of subtlety there will be a "mental pole" and a "physical pole" . . . But the deeper reality is something beyond either mind or matter, both of which are only aspects that serve as terms for analysis*." (Bohm, 1990, p. 285)

Fechner also contributed significantly to the German psychology of unconscious. cognition. However, his pioneering work on "unattended mental states" has not been paid due attention in academic circles (Romand, 2012). Even though he was clearly scientifically minded, he had spiritual ideas which were rather atypical even in the 19th century (and especially today in contemporary materialistic mainstream science)[36]. Fechner could be classified as a panpsychist (or perhaps panentheist), i.e., he argued that consciousness (or soul/psyche)[37] is a universal and primordial feature of all things. According to Fechner, all things express the same *anima mundi*, or world soul, a conception which is closely aligned with the Vedic concept of the "cosmic psyche" or

[36] However, Fechner's ideas resonated with William James' thinking. For instance, "the compounding of consciousness", a Jamesian idea which "postulates the theoretical possibility for individual entities within a conscious system of thought to 'know' the thoughts of others within the system" (Hawkins, 2011, p. 68). Fechner and James both explicitly rejected materialist accounts of the relationship between mind and brain (i.e., mind and matter). James experimented with the psychedelic Mescaline and nitrous-oxide and he was very interested in spiritual ideas, as evidenced by his classic book "The varieties of religious experience" (James 1842-1910, 1902). Moreover, James advocated a "radical empiricism" (James, 1976) which is incongruent with the prevailing materialistic paradigm which disregards extraordinary (first-person) qualitative experiences, for instance, those occasioned by naturally occurring "consciousness expanding" (Metzner, 2010) psychedelics which have been utilised for spiritual purposes for millennia in various cultures. That is, James was an advocate of a "science of subjective experience", a stance which become relevant in the subsequent discussion of complementarity (e.g., subjective vs. objective, the observer vs. the observed).

[37] The word psyche is etymologically derived from the ancient Greek ψυχή (psukhḗ, "mind, soul, spirit"). Hence, psychology is the study of the "mind, soul, and spirit" even though most psychologists are utterly unaware of this etymological definition. Moreover, they want to differentiate themselves from these "metaphysical/philosophical" concepts in order to appear as "hard/materialistic" scientists. They thereby neglect and extremely rich intellectual heritage which has deep historical roots which span many cultures and epochs.

Ātman[38] (Orme-Johnson, Zimmerman, & Hawkins, 1997). The "rise of the world soul theory in modern German philosophy" has been extensively discussed by historians of science (Zachhuber, 2015). Fechner argued that all of existence is interconnected through "spiritual nerves" or "long ropes" which constitute a unified web of existence made of light, gravity, and yet unidentified forces.[39] This idea reverberates with the ancient ontological concept of "dependent origination" or "dependent arising" (Sanskrit: प्रतीत्यसमुत्पाद Pratītyasamutpāda), which is a key concept, *inter alia*, in Hua-yen Buddhism (Cook, 1977). Dependent origination is conceptually associated with the quantum physical concept of entanglement[40] (e.g., violations of Bell inequalities, discussed later) and quantum holism (Bohm, 1990). In eastern philosophy, the concept is often illustrated with the visual metaphor of Indra's net[41] (Sanskrit: इन्द्रजाल Indrajāla), a concept which originated in early ancient Vedic cosmology (see Figure 3).

[38] From a linguistic point of view the Sanskrit word Ātman forms the basis for the German word "Atmen" which means "breathing". Recall the etymology of the word psychology: The ancient Greek word psukhḗ (ψυχή) or psyche means "life/soul/spirit" and also "breath". Likewise, the Chinese symbol for "spirit, soul" is 魂 which also means "breath". Hence, the linkage between "soul/spirit" and breath was formed independently by separate cultures. Thus defined, psychology is the study of "life/soul/spirit" and "breath", i.e., Ātman.

[39] According to contemporary theorizing in physics and cosmology, ordinary atomic matter constitutes only ≈ 5% of the observable Universe. The remaining 95% consist of dark matter (≈ 26%) and dark energy (≈ 69%), which are hitherto completely mysterious to scientists. These values are in themselves astonishing because they indicate numerically how limited our epistemic understanding regarding the fundamental ontology of the Universe really is. Therefore, Fechner's ideas about "yet unknown forces" is not as absurd as it might seem prima facie (especially to scientists who were conditioned in a materialistic worldview). As Sir Isaac Newton framed it: "What we know is a drop. What we don't know is an ocean". Epistemological humility is a true virtue (Richards, 1988).

[40] When quantum theory was approx.10 years old (around 1935) the concept of entanglement emerged (quantum theory was invented/discovered around 1925-26). Entanglement is one of the most mind-boggling concepts in quantum physics because it is so incongruent with our intuitions about reality and specifically causality. Two particles that interacted at some point in time in the past are interconnected in a "strange" way. That is, they remain interconnected even though there is no known physical medium through which that interaction can be explained. This was discovered by Einstein and he believed that this "wired" logical consequence of the mathematical formalism of quantum mechanics would proof its invalidity. That is, if the mathematical axioms of quantum mechanics allow for such an absurd phenomenon than it surely must be wrong. However, today we know that Einstein was wrong and this nonlocal interaction between particles can be exploited for real world applications as, for instance, quantum teleportation and quantum cryptography (discussed later).

[41] In Hinduism, Indra is a Vedic deity (Flood, 2007) and is the most dominant deity in the ten anthological books which comprise the Rigveda (the Sanskrit etymology of Rigveda is ऋग्वेद *ṛgveda* "praise, shine" and

"*Imagine a multidimensional spider's web in the early morning covered with dew drops. And every dew drop contains the reflection of all the other dew drops. And, in each reflected dew drop, the reflections of all the other dew drops in that reflection. And so ad infinitum. That is the Buddhist conception of the universe in an image.*" (A. Watts, 1969)

Figure 3. Indra's net is a visual metaphor that illustrates the ontological concepts of dependent origination and interpenetration (see Cook, 1977).

The notion of interrelatedness has deep implications for morality and ethics and it has been applied to social contexts, for instance, in a speech given by Martin Luther King Jr.:

"*It really boils down to this: that all life is interrelated. We are all caught in an inescapable network of mutuality, tied into a single garment of destiny. Whatever affects one destiny, affects all indirectly*." (King, M.L., 1967)

वेद *veda* “knowledge”). In Buddhism, Indra is a guardian deity (Gethin, 1998). An artistic digital 3D rendering of Indra’s net can be viewed under the following URL: https://upload.wikimedia.org/wikipedia/commons/e/ea/Indrasnet.jpg

The fractal nature of reality, as metaphorically[42] symbolised by Indra's net, was conceived long before Benoît Mandelbrot invented fractal mathematics (Gomory, 2010). Interestingly, a recent paper published in SCIENTIFIC REPORTS investigated and compared the scale-invariance of various network topologies using supercomputer-simulations. Specifically, the paper discusses the significant structural similarity between the network topology of galaxies in comparison to the neuronal network architecture of brains (in line with the alchemical quasi-fractal principle "as above so below)[43]. The authors suggest that "some universal laws might accurately describe the dynamics of these networks, albeit the nature and common origin of such laws remain elusive" (Krioukov et al., 2012). Interestingly in the context of interconnectivity and relatedness, recent studies with the naturally alkaloid Psilocybin (a partial 5-hydroxitryptamin agonist) indicate that insights into the interconnected nature of reality can be neurochemically induced in controlled experimental settings (Lyons & Carhart-Harris, 2018; MacLean, Johnson, & Griffiths, 2011; R. Watts, Day, Krzanowski, Nutt, & Carhart-Harris, 2017), but see Appendix A3 for further information.

In the context of the "universal psyche", Fechner was convinced that the psyche of plants[44] is no more related to their physiology/phytochemistry than the human psyche is linked to neurophysiology/neurochemistry (a notion which stands in sharp contrast with

[42] The metaphoric nature of Indra's net is in itself extremely interesting from a cognitive psychology point of view, especially in the context of "contextual metaphor theory" (Gibbs, 2011; Lakoff, 1993). However, a deeper linguistic analysis would go beyond the scope of this chapter and we refer the interested reader to the seminal book "Metaphors we live by" (Lakoff & Johnson, 1980).
[43] Interestingly, the "Gott-Li self-creating universe model" (Vaas, 2004) postulates and eternal fractal universe and thereby circumvents the antinomy associated with the infinite regress associated with causal models of cosmology, e.g., Big Bang theory (Germann, 2015b).
For more information regarding the fractal universe theory visit:
http://irrational-decisions.com/?page_id=2351
[44] Interestingly, "plant consciousness" (Barlow, 2015) has recently been discussed in the context of the "orchestrated objective reduction" (Orch-OR) theory of consciousness (Hameroff, 2013; Hameroff & Penrose, 1996, 2004) which postulates that consciousness originates from quantum processes in neuronal microtubule.

contemporary materialistic reductionism which predominates the neurosciences and psychology which attempt to reduce *qualia* to physiological processes). Fechner wrote: "*None of my limbs anticipates anything for itself … only I, the spirit of myself, sense everything that happens to me*" (as cited in Falkowski, 2007). This perspective has elements of Neo-Platonism[45] as well as of Spinoza and Leibniz. He published his philosophical views, *inter alia*, in a book entitled "*ZendAvesta: oder über die Dinge des Himmels und des Jenseits*" (ZendAvesta: or on the Things of Heaven and the Hereafter)[46]. A detailed discussion of Fechner's "inner psychophysics" goes beyond the scope of this thesis and would lead to Hinduistic scriptures in which many Fechnerian memes can be found back. For instance, Fechner wrote in "Die Tagesansicht" (cit., p. 243): "*At the bottom there is only one entity that appears different when observed from different standpoints …*" And in his classic work "Elemente der Psychophysik" (cit., vol. I, p. 4.) he wrote similarly:

"*Neither do two causal chains unknown to each other interfere in disorderly fashion with each other because there is only one causal chain that acts in one substance only but can be perceived in two ways, that is, from two standpoints*."

As alluded to before, the notion of complementarity[47] and holism[48] can be found back in interpretations of modern quantum physics, for instance, in the concept of "quantum

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[45] Plato stated the same idea a long time before Fechner: "*Therefore, we may consequently state that: this world is indeed a living being endowed with a soul and intelligence […] a single visible living entity containing all other living entities, which by their nature are all related*." (J. C. Wilson, 1889)
[46] Fechner's book is in the public domain and available under the following URL: https://archive.org/stream/zendavestaoderb01lassgoog#page/n17/mode/thumb
[47] A broad quantum physical definition of complementarity is that physical objects have binary (conjugate) pairs of (mutually exclusive) properties which can not be measured simultaneously. The paradigmatic example is the wave-particle duality (cf. Young's seminal double-slit experiment first performed in 1801).
[48] Similar concepts are currently revising our notions of evolution and biology. The "hologenome theory of evolution" (Rosenberg et al., 2009) emphasises the interrelatedness of organisms, especially in microbiology. Organism are no longer viewed as encapsulated entities but as mutually dependent "holobionts" (Leggat, Ainsworth, Bythell, & Dove, 2007). The central concept of "symbiogenesis"

holism", as advocated by the eminent British quantum physicists David Bohm (Bohm, 1990; Hiley & Peat, 2012; C. U. M. Smith, 2009) and Fritjof Capra (Capra & Mansfield, 1976; McKinney, 1988), *inter alia*.

Fechner wanted to scientifically demonstrate the unity between the psychological and the physical (i.e., the internal and the external, the observer and the observed, subject and object). He thought if he could demonstrate lawful reliable relations between these seemingly different realms this would prove his point. Fechner saw all living things as having a psyche and this gave him a particularly animated perspective of nature. Even though Fechner's work had an extraordinary impact on the development of psychology as a scientific discipline, his philosophical contemplations are largely left out of the academic discourse and the majority of textbooks on psychophysics do not mention this important aspect of his work. Ironically, his philosophical thoughts were the driving motives behind the development of psychophysics. One reason for the selectivity bias is that German is no longer understood by scientists outside of German-speaking countries (Scheerer, 1987) and Fechner's voluminous works have only been partially translated. Another reason might be that Fechner's ideas challenge the mainstream *status quo* of science and are therefore disregarded. Fechner himself argued that his "inner psychophysics" was much more important than his "outer psychophysics" even though the former did not receive much attention in academic circles (D. K. Robinson, 2010) and is not mentioned in most textbooks and those that mention it do not grasp its full significance. While Fechner's experimental work is widely acknowledged, his philosophical views would be rejected by the vast majority of psychologists even though they use Fechnerian methodologies in their own materialistic research agenda –

(Rosenberg & Zilber-Rosenberg, 2011) is reminiscent of the concept of interdependent arising discussed earlier.

a paradigm which Fechner actually tried to invalidate with his work.

In the first chapter of his "Elements of Psychophysics" which was published in 1860, Fechner explicates the motivation for his endeavour to connect psychology with physics. After all, the external world is a chaotic conglomerate of multifarious disordered physical processes and the human psyche is no more less chaotic in its intricate workings. The obvious question is: Why would one assume that there is a precisely quantifiable and reliable correlation between these external and internal processes? Fechner refers to the work of Weber and in his review of Webers work, he is the first to reference "Weber's law" and Chapter 9 of his "Elements of Psychophysics" is even titled correspondingly (Das Weber'sche Gesetz), thereby emphasizing the lawful relation between (physical) stimulus properties and (psychological) perception. Fechner's aim was to create laws of sensation, as opposed to Weber's work on discrimination. That is, Weber discovered the law of discrimination whereas Fechner primarily wanted to develop a law of sensation (cf. Boring, 1928). Hence, Fechner's approach is much more ambitious because he wanted to find the laws that govern how internal experience changes as a function of the physical properties of external physical stimuli. That is, how does our conscious experience[49] change when the external world changes. In other words, how does conscious perception vary as a function of the physical stimuli that impinge on a specific sensory modality. As a good empirical experimentalist, Fechner was keenly aware that one cannot investigate how physical reality changes the psyche as a whole but that one has to isolate specific aspect of physical reality in order to bring them under rigorous experimental control (i.e., the science of psychophysics employs a reductionistic approach and progresses gradually in

[49] Today, this first-person experience would be referred to as *qualia* (Jackson, 1982) due to its subjective qualitative nature, as opposed to the postulated "objectively" quantifiable nature of the physical world (a view which has been deeply challenged by quantum physics).

small increments). Hence, Fechner focused on the most elementary aspect of the psyche and that is sensation. He reasoned: If one can develop the laws of elementary sensations, then this is a first stepping stone in the hierarchy of understanding more complex psychological phenomena which are more complex than simple sensations. One could argue that the task of theoreticians is to look at the "bigger picture" whereas experimentalists have to focus on isolated phenomena, viz., global vs. local levels of analysis (even though both are mutually reciprocal). Fechner thus sought to develop a way in which he could experimentally investigate how "sensation magnitude" varies as a function of stimulus intensity. Fechner's law formalises exactly this: it quantifies the relationship between the magnitude of a physical stimulus and the consciously perceived intensity of the sensory experience.[50] This relation between stimulus and experience is logarithmic in nature, i.e., a stimulus varies as a logarithmic geometric progression (i.e. multiplied by a fixed factor), the corresponding magnitude of experience changes in a linear arithmetic progression (i.e. in additive fashion). Ergo, for multiplications in stimulus intensity, the intensity of experience is only additive. For example, if a given visual stimulus is increased by a factor of three (3 x 1), the associated perception increases by a factor of two relative to its original value (i.e., 1 + 1). If the same stimulus is again increased by a factor of three (i.e., 3 x 3 x 1), the associated perception is three times stronger relative to its original value (i.e., 1 + 1 +

[50] The relation between stimuli and sensation is what Fechner called "outer psychophysics" and this forms the main pillar of contemporary psychophysics. However, Fechner regarded "inner psychophysics" as much more important. Inner psychophysics focuses on the relation between neuronal (physical) processes and sensations. This topic has not received much attention in psychophysics (Murray, 1993) and it is related to the mind-body problem in philosophy of mind which is much more complicated than the outer psychophysics program. The question is, how does "objectively" quantifiable electrochemical transduction of action potentials (a physical process) give rise to subjective first-person experiences (quale). Currently, science cannot even begin to answer this central question even though it is crucial in order to understand really understand sensation and perception in psychophysics (again – the fundamental question concerning the relation between the observer and the observed). Inner and outer psychophysics can be regarded as complementary (J. C. Baird, 1997).

1). Fechner's law and Weber's law are two essential formulae in perceptual/sensory psychology[51] (J. C. Baird, 1997). However, later, both have been revised and refined. Weber's law becomes imprecise when the absolute perceptual threshold is approached, and the same imprecisions are encountered for very intense stimuli. Fechner's law, on the other hand is a good description of brightness perception but it does not hold for loudness (i.e., loudness perception grows exponentially in proportion to stimulus intensity as opposed to logarithmically). In the 1950s Harvard psychophysicist Stanley Smith Stevens formulated a power law of the relation between the magnitude of a physical stimulus and its perceived psychological experience which is more generalizable across sensory modalities.

Equation 3. Stevens's power law.

$$\psi(I) = kI^a$$

where *I* denotes the magnitude of the stimulus, $\psi(I)$ signifies the subjectively perceived magnitude of the sensation evoked by the stimulus, and *a* is an exponent associated with the type of sensory stimulation, and *k* is a constant that depends on the specific metric. That is, the magnitude of perception increases as an exponent (i.e., power) of stimulus intensity (the exponential factor can be >1). Hence by varying the exponent, Steven's power law can express exponential and logarithmic proportionality between stimulus and perception. Hence, it can reproduce Weber's and Fechner's law and it can account for situations which the former are unable to handle (i.e., it is more generalisable and can be regarded as a "covering law"). Stevens law has also been a subject of extensive criticism and revision. For instance, Robert Duncan Luce observed that "by introducing

[51] Interestingly, there is a new branch in the literature on public finance which hypothesises that the Weber–Fechner law can explain the increasing levels of public expenditures in mature democracies. Election after election, voters demand more public goods to be effectively impressed; therefore, politicians try to increase the „magnitude" of this „signal of competence" – the size and composition of public expenditures – in order to collect more votes (Jorge Reis Mourao, 2012).

contexts such as background noise in loudness judgements, the shape of the magnitude estimation functions certainly deviates sharply from a power function" (Luce, 1990, p. 73; cf. Luce, 2002). Furthermore, in order to utilise the scaling procedures in the standard way as advocated by Stevens, several fundamental conditions that have to be met empirically (Luce, 2002). One of these axioms is termed "commutativity" or "threshold proportion commutativity" (Narens, 1996, Axiom 4, p. 114). Specifically, the commutativity axiom only holds true if the outcome of two successive adjustments (e.g., 3x as loud and 4x as loud) is independent of the order in which these adjustments are made. The concept of commutativity will be discussed in greater detail in the context of quantum probability where it plays a crucial role. The fact that the same target luminance can elicit different perceptions of brightness depending on the context has puzzled psychophysicist ever since. More recently, it has been argued in a paper published in the Proceedings of the National Academy of Sciences "that brightness is determined by the statistics of natural light patterns implies that the relevant neural circuitry is specifically organized to generate these probabilistic responses" (Yang & Purves, 2004). However, the probabilistic framework which is utilised to account for perceptual contextuality is Kolmogorovian in nature and therefore unable to account for noncommutativity effects in a parsimonious fashion. Moreover, it is implicitly assumed that the perceptual system itself is always in a discrete state, independent of the probabilistic nature of natural light patterns (cf. Hoffman, 2016). We will subsequently address this assumptions in the context of noncommutativity in visual judgments.

To conclude the brief discourse on the history and goals of psychophysics it should be emphasised that this academic discipline is by far the most exact and reproducible area of psychology. The data obtained in psychophysics experiments has usually such a high degree of quantitative accuracy that it is more reliable and replicable than physiological data associated with the same sensory modalities (e.g., neurophysiological measurements). From a methodological point of view, it can oftentimes be reasonably questioned whether the standard hypothetico deductive-nomological model (also known as covering law model or Popper-Hempel model) is appropriate for many aspects of psychological research. Psychophysics is an area of psychology were the application of this nomological approach to hypothesis testing is most effectively justifiable because the "explanans" are precisely defined. Psychophysics has demonstrated that the sensitivity of the visual system is as low as five quanta at the photoreceptor level (D. Robinson, 2001), and that the auditory system is able to detect acoustic signals at the level of Brownian-motion. Hence, psychophysics is an exact, quantitative, and nomological branch of psychology. Contemporary psychophysics focuses on "sensation and perception" and this dichotomy has been fittingly described as "the complementarity of psychophysics" (J. Baird, 1997). The psychophysical complementarity also refers to what Fechner called "inner" and "outer psychophysics" or as Stevens (1975, p. 7) put it, the "inner world of sensation" and the "outer world of stimuli". We will discuss this deep philosophical concept in more detail in the next section because the complementarity principle is central to quantum physics and quantum cognition.

1.6 A brief history of the evolution of the "complementarity" meme in physics

It was a pivotal turning point for physics when Nils Bohr first introduced his formulation of the idea of complementarity to his numerous colleagues. This historical event took place at the International Congress of Physics in September 1927 in Como, Italy and the world's most eminent physicists were in the audience: Max Born, Enrico

Fermi, John von Neumann, Wolfgang Pauli, Max Planck, Werner Heisenberg, Eugene Wigner, Louis de Broglie, to name just a few. However, Albert Einstein was noticeably absent for some unbeknown reason (Holton, 1970).

The idea of complementarity fundamentally transformed physics. One of the crucial points Bohr emphasised concerned "the impossibility of any sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear" (Bohr, 1961).

In a theme issue of the journal DIALECTICA edited by Wolfgang Pauli and published in 1948 compiles various seminal papers on complementarity by eminent physicists. Bohr also contributed an article to this special issue entitled "On the notions of causality and complementarity" (Bohr, 1948) in which he discusses the dialectic complementarity mode of description and the impossibility to objectively separate "between behaviour of the atomic objects and their interaction with the measuring instruments defining the conditions under which the phenomena appear" (Bohr, 1948, p.312).

Interestingly, Bohr was a cousin of the famous Danish psychologist Edgar Rubin who is famous for his eponymous Rubin's Vase (E. Rubin, 1915), see Figure 4. This ambiguous visual stimulus is today still widely used in research on bistable perception in psychology and neuroscience (e.g., Hasson, Hendler, Bashat, & Malach, 2001; Qiu et al., 2009; X. Wang et al., 2017). Interestingly from a history of science point of view, it was Rubin who introduced Bohr to the concept of complementarity. Both were members of the club "Ekliptika" (see Figure 5). Rubin in turn adopted the idea from the writings of the late William James who wrote about complementarity in Chapter 8 in his timeless classic "Principles of Psychology" (James, 1890b). While Rubin focused on perceptual complementarity, Bohr was primarily concerned with epistemological complementarity (Pind, 2014) and much of his later writings were concerned with this topic. Hence, from this historical vantage point, the quantum cognition paradigm is bringing the meme of complementarity (which originated in psychology and spread to change the fundamentals of physics) back to its roots.

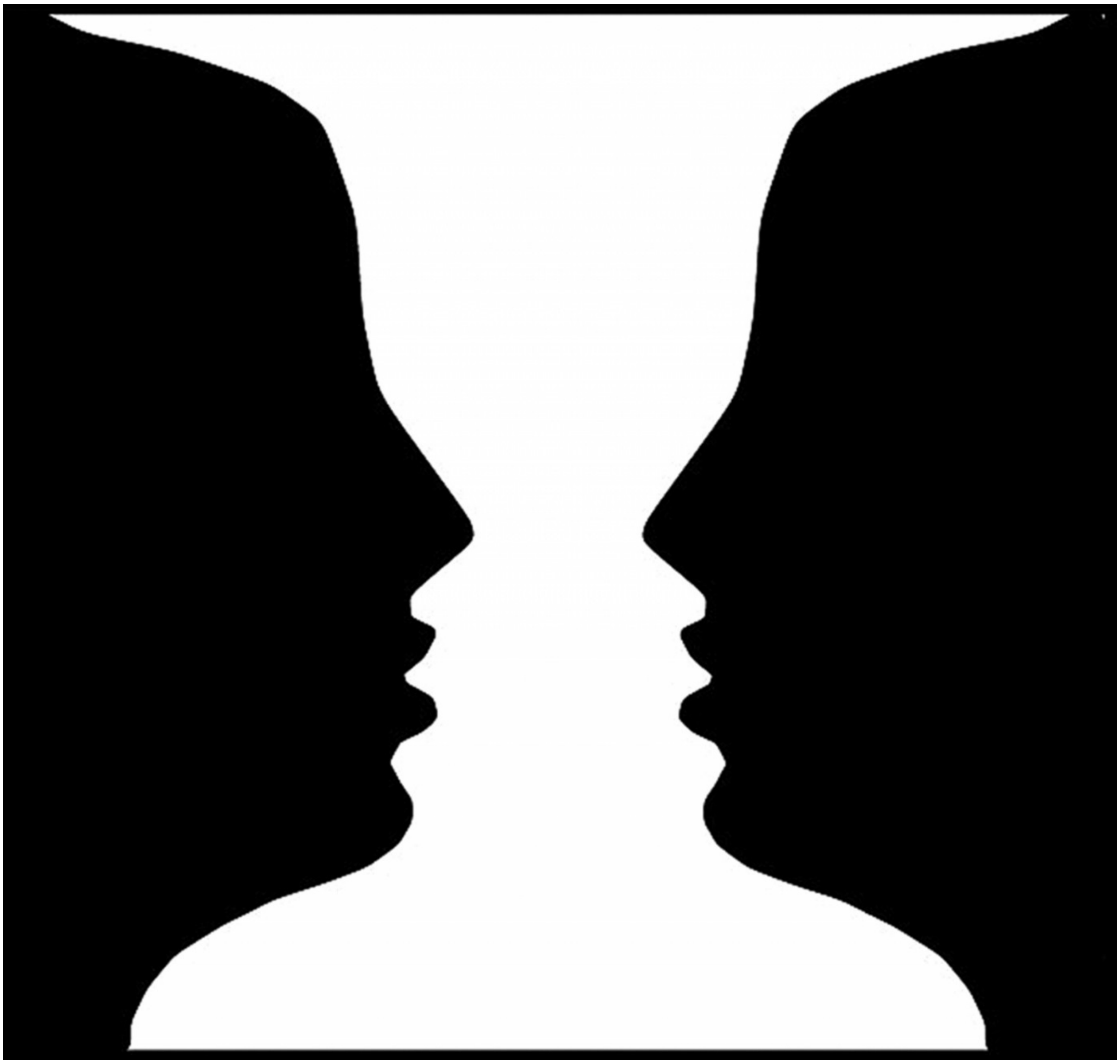

Figure 4. Rubin’s Vase: A bistable percept as a visual example of complementarity-coupling between foreground and background.

In an interview[52] with Thomas Kuhn[53] which took place in 1962, Bohr stated:

I was a close friend of Rubin, and, therefore, I read actually the work of William James. William James is really wonderful in the way that he makes it clear—I think I read the book, or a paragraph, called —. No, what is that called?—It is called ''The Stream of Thoughts,'' where he in a most clear manner shows that it is quite impossible to analyse things in terms of—I don't know what one calls them, not atoms. I mean simply, if you have some things…they are so connected that if you try to separate them from each other, it just has nothing to do with the actual situation. I think that we shall really go into these things, and I know something about William James. That is coming first up now. And that was because I spoke to people about other things, and then Rubin advised me to read something of William James, and I thought he was most wonderful."

The significance of complementarity beyond the domain of physics has been discussed in greater detail by Atmanspacher, Römer, & Walach (2002). The complementarity principle is closely related to the concepts of entanglement, superposition, noncommutativity, and the stipulated collapse of the wave-function. In fact, "quantum noncommutativity can be regarded as a mathematical expression of the complementarity principle" (Plotnitsky, 2016).

[52] The full transcript of the interview is available on the homepage of the American Institute of Physics under the following URL: https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4517-5

[53] Interestingly, Thomas Kuhn made use of ambiguous visual stimuli in his own work to demonstrate the perceptual change that accompanies a paradigm-shift. He used the "duck-rabbit" (a bistable figure created by the psychophysicist Joseph Jastrow and popularised by Ludwig Wittgenstein), as a visual metaphor to illustrate that a paradigm-shift can cause the cogniser to perceive the same information in a completely different way (see Appendix A7 for an example and a discussion). The complementarity principle was thus utilised in the context of the perception of seemingly incompatible scientific paradigms. That is, it illustrates the Kuhnian concept of incommensurability which is of great relevance for the discussion of the perceived dichotomy between mind and matter. Moreover, the inability to entertain multiple viewpoints simultaneously is of great pertinence for discussion of interdisciplinarity, e.g., psychology and physics (mind/matter) can be regarded as complementary.

Figure 5. Photograph of Niels Bohr and Edgar Rubin as members of the club "Ekliptika" (Royal Library of Denmark).

From left to right: Harald Bohr, Poul Nørlund, Edgar Rubin, Niels Bohr and Niels-Erik Nørlund (Royal Library, Copenhagen[54]).

When Bohr received the prestigious Danish "Order of the Elephant" (a distinction normally reserved for royalty) he emphasised the importance of the complementarity principle. Bohr choose to wear the ancient Chinese Yin & Yang symbol ☯ on his coat of arms together with the Latin slogan "*Contraria sunt complementa*" (opposites are complementary), see Figure 6. The resemblance between the Yin and Yang symbol and the ambiguous figures studied by Rubin is remarkable. Moreover, various interdisciplinary scholars maintain that nonduality between mind and matter (psyche vs. physis, percipient vs. perceived, observer vs. observed, inner vs. outer, etc. pp.) is a

[54] Associated URL of the file in the digital Royal Library of Denmark: http://www.kb.dk/images/billed/2010/okt/billeder/object73704/da/

fundamental pillar of Advaita Vedānta, Mahayana/Madhyamaka Buddhism, and Neo-Platonism (e.g., Plotinus), *inter alia*.

Figure 6. Escutcheon worn by Niels Bohr during the award of the “Order of the Elephant”.

In 1947 Bohr was awarded with the “Order of the Elephant” (*Elefantordenen*), Demarks highest-ranked accolade. Bohr chose a “coat of arms” which was embroidered with the Buddhistic Yin & Yang symbol in order to emphasise the centrality of nonduality and complementarity[55] in his work on quantum physics. Chinese Buddhism is an offshoot of early Hinduism, the womb of the ancient nondual philosophical school of Advaita

[55] Interestingly from both a visual science and physics point of view, when light interacts with the eye the wave-particle duality resolves, that is, observation collapses the superpositional state into a determinate eigenvalue. In this context, Einstein wrote the following on the complementarity of physical descriptions: “*It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do*.” (Einstein & Infeld, 1938, p. 278)

Vedānta[56] which is based on a highly sophisticated and extensive logic system (Gabbay & Guenthner, 2014; Nicholson, 2007). Nils Bohr writes: "Altogether, the approach towards the problem of explanation that is embodied in the notion of complementarity suggests itself in our position as conscious beings and recalls forcefully the teaching of ancient thinkers that, in the search for a harmonious attitude towards life, it must never be forgotten that we ourselves are both actors and spectators in the drama of existence" (Bohr, 1950, p.54).

Applied to the dichotomy between science and mysticism described by William James (see introduction), the complementarity principle entails that science and mysticism are not mutually exclusive but both necessary to complete the circle of human understanding.

1.7 Quantum cognitive science?

All known information processing systems are physically embodied (i.e., they are grounded in physical substrates). From a reductionist point of view, the underlying physics of all information processing systems is consequently ultimately quantum-mechanical in nature. It follows deductively[57] that science has to reconsider information processing and computation in the light of recent evidence from quantum physics. Information processing and computation play a major role in psychology, neuroscience, and many other scientific disciplines (e.g., computational cognitive science (Sun, 1950),

[56]According to Advaita Vedānta, consciousness and material reality do not exist in separation. This schism, is an illusion or Māyā (Bhattacharji, 1970; Dabee, 2017). That is, the subject/object divide is also part of Māyā or "mere appearance". Beyond the perceived duality is what quantum physicist John Hagelin calls "the unified field" or "string field"– pure abstract self-awareness which forms the nondual basis for *all* of existence, material and immaterial (Hagelin & Hagelin, 1981).

[57] One can construct a logically valid syllogistic argument in order to deduce the conclusion that quantum physics is necessarily relevant for cognitive/computational processes and their neural correlates.

computational neuroscience (Sejnowski, Koch, & Churchland, 1988), computational biology , etc. pp.). For instance, cognitive modelling is concerned with computational models of cognition. These models assume “cognitive completeness” (Yearsley & Pothos, 2014). Cognitive completeness implies that behaviour (e.g., perceptual judgments) can be explained in purely cognitive terms without the invocation of neural correlates. This is an implicit assumption of almost all cognitive models, otherwise cognitive science would be forced to constantly integrate the complexities of neurophysiology and neurochemistry into its modelling efforts (of course there are exception). *In sensu lato*, cognitive completeness is embedded in the notion of “multiple levels of description and explanation” (Coltheart, 2010; Perfors, 2012).

In the last century, quantum physics discovered extraordinary phenomena which shed new light on the fundamental workings of reality. Among these phenomena are, for instance, the concepts superposition, complementarity, and entanglement (Atmanspacher et al., 2002). Besides their purely theoretical (and ontological) relevance, these counterintuitive “strange” principles can be utilised for various practical purposes. Real-world applications include, quantum encryption (Bernstein & Lange, 2017), quantum communication (Zhang et al., 2017), and quantum computation (Divincenzo, 1995), quantum teleportation (Ren et al., 2017), *inter alia*. For instance, entanglement (see Bell’s theorem) can be utilised for extremely efficient transfer of information (faster than the speed of light) and it has been convincingly argued that the next generation of the internet (the “quantum internet” (Kimble, 2008; C. R. Monroe, Schoelkopf, & Lukin, 2016; Pirandola & Braunstein, 2016)) will be based on the principle of nonlocal entanglement, i.e., quantum nonlocality (Popescu & Rohrlich, 1992, 1994). However, the significance of these findings has not yet been realised by the majority of cognitive and neuroscientists. Empirical research has clearly demonstrated (i.e., beyond any reasonable doubt) that quantum computational resources exists in nature and that they can be successfully employed for various pragmatic purposes. However, hitherto these principles have not yet been given their due in mainstream psychology (and neuroscience) and many researchers would argue that the findings made by quantum physicists do not apply to cognitive processes (that is, they are *a priori* assumed to be restricted to the physical microdomain). However, we argue that the "burden of proof" (Hahn & Oaksford, 2007) rests on the side of those who argue that QM principles do not apply to cognition: Why would the cognitive system not make use of these extremely powerful computational resources?

An essential concept in this context is the qubit. The origination of the term qubit is ascribed to Schumacher (1995) who proposes the term "quantum bits" or "qubits" in his seminal paper entitled "quantum coding". A qubit is a unit of quantum information (a two-state quantum-mechanical system) and it can be regarded as an analogon to the binary bit. By contrast to the classical bit, a qubit can be in a superpositional state. The mathematical representation of a qubit is given in Equation 4, where α and β denote probability amplitudes

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Equation 4. Mathematical representation of a qubit in Dirac notation.

Conventionally quantum states are represented in Dirac notation (Equation 4) in which computational basis states are enclosed in bra (|)–ket (⟩) notation, i.e., $|0\rangle$ and $|1\rangle$. A geometrical (and more intuitive) representation of a qubit is provided in Figure 7.

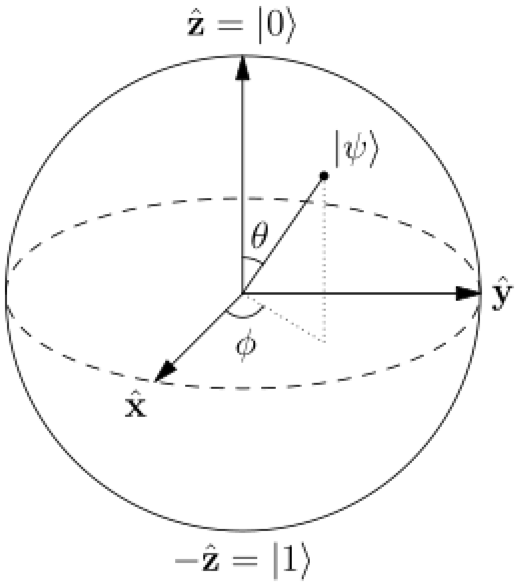

Figure 7. Bloch sphere: a geometrical representation of a qubit.

Note: The qubit is a two-state system which can be in a superpositional state similar to Youngs classical experiment (Østgård et al., 2014).

The qubit requires a completely new way of thinking about information and computation. A qubit is a two-level quantum mechanical system and it can be in a superpositional state, i.e., multiple states at the same time. Mathematically, a quantum logical qubit state can be written as a linear combination (viz., superposition) of $|0\rangle$ and $|1\rangle$. Moreover, a qubit can be visually represented as a Bloch sphere which is eponymously named after its inventor (Bloch, 1946). Fascinatingly, a single qubit can in principle carry the information of all libraries in the world (Muthukrishnan & Stroud, 2000), viz., continuous-valued quantum information in a linear superposition (the problem is how to measure the information without destroying it via collapse of the superposition caused by the measurement).

The primary difference between one- and two-qubit states is their dimensionality. While a one-qubit state has two dimensions a two-qubit state has four dimensions. This is the case because in mathematics the tensor product $A \otimes B$ (where $\otimes$ signifies the tensor product, also known as Kronecker product[58]) of two vector spaces A and B forms a new higher-dimensional vector space which has a dimensionality equal to the product of the dimensions of the two factors. In linear algebraic notation this can be written as follows:[59]

$$00 \equiv \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix}, 01 \equiv \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\\0\\0\end{bmatrix},$$
$$10 \equiv \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\end{bmatrix}, 11 \equiv \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}.$$

However, the two-qubit states which cannot be simply reduced to the Kronecker product of single-qubit states because they are in an entangled state and the contained information is not reducible to the individual constituent qubits (i.e. the whole is more than the sum of its parts). The contained information is rather stored in the correlation between the two states, i.e., it is non-local quantum information (Nielsen & Chuang, 2010). This non-locality of information is a crucial criterion which distinguishes quantum computation from classical computation. Moreover, this type of non-local information storage is the basis of various quantum protocols, for instance quantum teleportation (Gottesman & Chuang, 1999).

A qutrit is defined as a unit of quantum information that is composed of the superposition of three orthogonal quantum states (Klimov, Guzmán, Retamal, & Saavedra, 2003). While a qubit is analogous to a classical bit, a qutrit is analogous to the

[58] Note that the Kronecker product is not identical to usual matrix multiplication which is a different mathematical operation.
[59] Matrix-notation adapted from Microsoft's Quantum Development Kit: https://docs.microsoft.com/en-us/quantum/quantum-concepts-5-multiplequbits

classical trit (trinary digit), for instance as utilised by ternary[60] computers based on ternary logic (aka. 3VL) (Putnam, 1957). Consequently, a multiqubit quantum computer with ≈300 entangled qubits could instantaneously compute more calculations than there are atoms in the known universe. However, due to decoherence, superpositions are extremely delicate. The problem lies in measuring the contained information. As soon as an invasive measurement on the system is performed, the superpositional states collapse into an eigenstate (environmentally-induced decoherence) and the information is lost.[61] In sum, superposition is an essential property which is utilised for quantum computation and it also appears to be applicable to models of cognition (Busemeyer & Bruza, 2012). Moreover, the future of the rapidly developing fields of machine learning and artificial intelligence is likely based on these extremely powerful quantum computational principles which require a radically new way to think about information (Biamonte et al., 2017; Dunjko & Briegel, 2017; Prati, 2017). Therefore, cognitive psychology is now carrying the burden of proof: Why should nature not make use of these extremely effective quantum-principles in the domain of cognitive processes? Most models of cognition are strongly influenced by the principles of digital binary computation (Piccinini & Bahar, 2013), although some argue that "cognition is not computation"[62] (Bringsjord & Zenzen, 1997). A classical bit can adopt two possible states (i.e., binary states) usually symbolised as 0 and 1 (but more generally "true" or

[60] For instance, in "The art of computer programming" Donal Knuth (creator of TeX which forms the basis of LaTeX) explains that in balanced ternary, every digit takes on one of 3 values, i.e., [−1, 0, +1] (which can be more parsimoniously notated as [− ,0, +]). In the context of ternary notation, he also writes that "Positional number systems with negative digits have apparently been known for more than 1000 years in India in Vedic mathematics" (Knuth, 1973, p. 192).

[61] First attempts have been made to create qudits which, in contrast to two-state qubits can have multiple states simultaneously. A qudit based quantum computer with two 32-state qudits, could compute as many calculations as 10 qubit quantum computer, thereby speeding-up computation and significantly reduce problems associated with the delicate entanglement of multi-qubit systems (Neeley et al., 2009).

[62] Specifically, the authors argue that "computation is reversible; cognition isn't; ergo, cognition isn't computation" (Bringsjord & Zenzen, 1997, p. 285). The irreversibility of cognitive processes might be rooted in the stochastic nature of quantum processes (Aaronson, Grier, & Schaeffer, 2015; cf. Yearsley & Pothos, 2014).

“false” or any other dichotomous notation, e.g., cats and dogs, as the physical substrate in which the bit is realised is not important. This substrate independence is known as multiple realizability, for a discussion of this fundamental concept see Shapiro (2000). This implies that computation should be treated as logical abstraction – what is important is software (logic) not the physical substrate (hardware).

Alan Turing wrote:

“The [Babbage Engine's] storage was to be purely mechanical, using wheels and cards. The fact that Babbage's Analytical Engine was to be entirely mechanical will help us rid ourselves of a superstition. Importance is often attached to the fact that modern digital computers are electrical, and the nervous system is also electrical. Since Babbage's machine was not electrical, and since all digital computers are in a sense equivalent, we see that this use of electricity cannot be of theoretical importance. ... If we wish to find such similarities we should look rather for mathematical analogies of function.”

Richard Feynman argued in his lecture series on quantum computation that Turing’s arguments were impeccable but that he did not consider substrates that behave according to the “strange” laws of quantum logic. The crucial point is that it has become very clear that classical notions of physics are no longer defendable on empirical grounds (e.g., local realism) (Giustina et al., 2015; Hensen et al., 2015; Wiseman, 2015). All information processing systems are embodied in some form of physical substrate. Given that those physical substrates ae governed by the laws of quantum mechanics, it follows that classical (Newtonian) notions of computation have to be revised (and in fact are currently being revised) in the light of insight derived from quantum physics. For instance, Google and NASA are currently heavily investing into quantum computation and quantum AI (both are grounded on quantum logic). In sum, quantum computational principles will significantly speed up a large array of computational processes (Rønnow et al., 2014) and might turn out to be a driving force for the continuation of Moore's law (Lundstrom, 2003; G. E. Moore, 1965). Superposition and entanglement are pivotal concepts in quantum information and quantum computing (Boyer, Liss, & Mor, 2017). Quantum information and computation are closely related to quantum cognition, as cognition is understood to be information processing. Many cognitive and neuroscientists believe that cognition is essentially a form of computational, i.e., it can be modelled mathematically by utilising various computational principles (i.e., Bayes' rule). Therefore, it is obvious that cognitive scientists should consider quantum computational principles which do not obey Bayes' rule (which is based on Kolmogorov's probability axioms). The same quantum computational principles are also important for neuroscience and particularly (neuro)computational neuroscience and artificial intelligence. Currently, neurons are almost exclusively modelled as binary states (firing vs. resting), even though several researchers are now beginning to integrate quantum approaches into their efforts (Schuld, Sinayskiy, & Petruccione, 2014). From a quantum perspective, neurons can be modelled as superpositional states. Given that neurons are thought to underpin all of cognition (at least in a reductionist materialism framework) this has implications for the high-order cognitive processes and computational models of cognition which are based on these neurocomputational processes.

1.8 Perceptual judgments under uncertainty

Random walk models (e.g., Ratcliff & Smith, 2004; Usher & McClelland, 2001) which focus on reaction times in various decision scenarios assume that evidence (information) is accumulated diachronically (over time) until a specific critical decision-threshold (or criterion) is reached (Busemeyer & Bruza, 2012). In these models, the weights associated with each option increases chronologically in a progressive manner. However, at each discrete point in the temporal sequence the system is assumed to be in a definite determinate state. This state can in principle be accessed by taking a measurement. Moreover, it is assumed that the act of measuring does not influence the state under investigation. That is, classical models presuppose that 1) a given system is consistently in a specific state (even though the observers' cognition of this state might be uncertain) and 2) that this state is independent of the measurement operation which is performed on the system. *Prima facie*, these postulates seem intuitive and logically valid. How else could one build a model of a system if it is not in a definite (stable) state at any point in time? And how else could one gain "objective" information about the state of the system if not via independent (interference-free) measurements which "read-out" the actual state of the system?

However, both assumptions stand in sharp contrast with one of the main ideas of quantum probability (QP) theory which provides the axiomatic basis of quantum theory. A fundamental insight derived from quantum theory is that taking a "physical measurement" of a "physical system" actively creates rather than passively records the property under investigation. By contrast, classical theories assume that taking a measurement merely reads out an already pre-existing state of a system.

Moreover, QP is incompatible with the classical notion that a given system (be it physical or psychological) is always in an *a priori* determinable state at any point in time. By contrast, QP allows for the possibility that a system can be in a superpositional state in which n possibilities can exist simultaneously. It is only when a measurement is taken that these undetermined potentialities collapse into determinate actualities.

The collapse of the wave-function Ψ is caused by interactions with the environment, a process known as decoherence, i.e., the destruction of interference (Zurek, 1994). This environment-induced collapse causes a loss of information, i.e., entropy.[63] In other words, decoherence is the transition from a quantum state to a classical state, a process called "Einselection" (Zurek, 2003). Thus, Einselection imposes classicality via a drastic reduction of the dimensionality of the Hilbert space, in other terms, it creates coherence from decoherence (Zurek, Habib, & Paz, 1993). That is, "classical structure of phase space emerges from the quantum Hilbert space" and "in measurements, Einselection replaces quantum entanglement between the apparatus and the measured system with the classical correlation" (Zurek, 2003, p. 715). Our foregone discussion of the concept of complementarity in visual perception illustrates this point. The Rubin's vase can be regarded as a bistable superpositional quantum state. The visual percept is in a superpositional state and it is only when a measurement is taken (i.e., an observer observes the stimulus) that the superposition collapses into a mutually exclusive "either/or" eigenstate (the dominance of either foreground or background) caused by the process of Einselection. Similarly, the Necker cube (Necker, 1832) has been described in terms of quantum superposition and temporal nonlocality[64] (Atmanspacher & Filk, 2010; Atmanspacher, Filk, & Römer, 2009; Conte, Khrennikov, Todarello, Federici, Mendolicchio, et al., 2009) and the quantum Zeno effect (Asher Peres, 1980) has been successfully applied to model the switching rates between bistable (ambiguous) visual percepts (Atmanspacher & Filk, 2013; Atmanspacher, Filk, & Römer, 2004).

We created two websites with additional information. One contains a dynamic

[63] Entropy is a function of t (time evolution of the system) and a functional of the systems initial state. The entanglement between the system and the environment can be calculated by computing the entropy using the following intuitive algorithm (but see Zurek et al., 1993):
$\mathcal{H}_{\Psi}(t) = -\mathrm{Tr}(\rho_{\Psi}(t) \log \rho_{\Psi}(t))$

[64] Locality describes the notion that a given event X cannot cause a change in Y in less time than $T = D/c$, where T signifies time, D is the distance between X and Y, and c the (constant) speed of light, and.

“Adobe® Shockwave Flash” animation of the Necker cube from a quantum cognition perspective[65]. The other contains several digital animated artworks we designed and is entitled “Necker Qbism: Thinking outside the box – getting creative with the Necker cube”, in analogy with the superpositional quantum qubit and the concept of simultaneity in cubism (Fry, 1988).[66]

Briefly, Atmanspacher et al. applied the concept of “temporal nonlocality” (Brunner, Cavalcanti, Pironio, Scarani, & Wehner, 2014) to the perception of bistable stimuli (i.e., the Necker cube). Temporal nonlocality implies that “events cannot be uniquely fixed in time” and it is based on temporal Bell inequalities (or Leggett–Garg inequalities). The exact definition of TBI goes beyond the scope of this chapter (but see Eberly, 2002). Temporal Bell inequalities are particularly important for quantum-like context effects, quantum entanglement, and the Kochen-Specker theorem (Santos, 2016). Within the context at hand, temporal Bell inequalities are most pertinent when multiple measurements are performed at different points in time. According to physical realism[67] (A. J. Leggett, 2014), a given system with two or more possible states is at all times in a definite (fixed) state. Such a realist system satisfies the temporal Bell inequality (Yearsley & Pothos, 2014). In the history of science, the violation of TBI is one of the most important findings of the 20th century. The violation of TBI has first been empirically demonstrated by Aspect, Grangier, & Roger (1981) and various independent labs replicated and extended this paradigm-changing experimental

[65] URL associated with the “Quantum Necker cube”: http://irrational-decisions.com/?page_id=420
[66] URL of the “Necker Qbism gallery”: http://irrational-decisions.com/?page_id=1354
[67] Physical realism postulates a mind-independent reality that is composed of physical entities that are located in space and time, and interact causally with each other (Ellis, 2005). The concept is crucial for an understanding of quantum physics as it forms the basis for many discussions among scholars, e.g., the prototypical Einstein vs. Bohr debate on epistemology and ontology (Mehra, 1987).

finding.[68] The wide ramifications of this scientific finding are staggering because the violation of TBI negates the fundamental concept of "local causality" – thereby ruling out a large class of previously widely accepted physical models (Yearsley & Pothos, 2014), namely those which are based on local realism. However, in physics, local realism has now been conclusively rejected (Giustina et al., 2015; Gröblacher et al., 2007; Hensen et al., 2015). To those scientists who still persistently "believe" in an objectively existing material reality[69] we recommend the concise NATURE article entitled "The mental universe" authored by Richard Conn Henry, academy professor of physics and astronomy at Johns Hopkins University (Henry, 2005) and the more recent NATURE paper "Death by experiment for local realism" (Wiseman, 2015). In yet another NATURE paper the following explicit statement has been formulated: "*Most working*

[68] Critics argue that the experiments might be confounded (e.g., by a loopholes/additional assumptions). However, recent experiments successfully addressed these potentially confounding loopholes (e.g., Giustina et al., 2015) and provide strong empirical evidence of TBI violations, thereby paving the way for implementing "device-independent quantum-secure communication" (Hensen et al., 2015). A even more recent cutting edge experiment performed a "Cosmic Bell Test" by investigating violations of Bell inequalities in polarization-entangled photons from distant Milky Way stars in real-time (Handsteiner et al., 2017). The experiment confirmed the quantum theoretical prediction regarding statistical correlations between measurements and provides further evidence against the classical local-realist theory. The authors concluded that their experimental design rules out "any hidden-variable mechanism exploiting the freedom-of-choice loophole" because it "would need to have been enacted prior to Gutenberg's invention of the printing press, which itself predates the publication of Newton's Principia". Interestingly, the researchers report p-values $< 1.8 \times 10^{-13}$ in support of their conclusion (Handsteiner et al., 2017, p. 4), indicating that frequentist p-values are unfortunately still relevant in cutting-edge physics. The reporting of such extremely small p-values (in the abstract) is misleading, as it capitalizes on the "replication fallacy", i.e., the widely shared fallacious belief that small p-values indicate reliable research (e.g., Amrhein, Korner-Nievergelt, & Roth, 2017).

[69]Bishop Berkeley's statement "*esse est percipi (aut percipere)*" — to be is to be perceived (or to perceive) is relevant in this context. Samuel Johnson famously asserted in 1763 to have disproven Berkeley's nonmaterialistic stance by kicking a rock and he is known to have said "I refute Berkeley thus", a *non sequitur* (cf. Priest, 1989; "Primary qualities are secondary qualities too"). This logical fallacy goes by the name "*argumentum ad lapidem*" (Latin for "appeal to the stone") (Winkler, 2005) as it is no valid argument but merely superficially dismissing Berkley's claim without providing any reasons (Pirie, 2007). An example of this type of logical fallacy follows:
Person 1: Under the code name MK-Ultra, the CIA conducted illegal drug experiments on countless nonconsenting human being to investigate mind control techniques which resulted in several deaths.
Person 2: This is just a conspiracy theory!
Person 1: Why do you think so?
Person 2: It is obviously just paranoia.
In this example of an "appeal to the stone" fallacy, Person 2 provides no logical reasons or facts. Person 2 merely asserts that the claim is absurd and therefore commits the same logical fallacy as Berkley's argumentative opponent..

scientists hold fast to the concept of 'realism' - a viewpoint according to which an external reality exists independent of observation. But quantum physics has shattered some of our cornerstone beliefs." The authors go on and state that experimental evidence (i.e., violation of Bell inequalities) has rendered "local realistic theories untenable" (Gröblacher et al., 2007).[70] Similarly to the breakthrough in quantum physics, an experimental demonstration of a TBI violation in psychological observables would herald a paradigm-shift in psychology because such a finding would rule out a large class of cognitive models which assume that cognitive systems are always in a deterministic state (Yearsley & Pothos, 2014). Experimental approaches that could falsify TBI in the context of visual perception have already been formulated (Atmanspacher & Filk, 2010). The implications such an empirical discovery would have for psychology and neuroscience cannot be overemphasised as the violation of BI is one of the most thought provoking finding physics has ever made. The rejection of local realism is not only highly counterintuitive, it might also "feel" very uncomfortable because our common-sense worldview is firmly anchored in this most constitutive paradigm. Such a finding would certainly cause severe cognitive dissonance in the minds of majority of scientists (Festinger, 1957, 1962). That is, if results from quantum physics challenge our most fundamental beliefs and force us to rethink reality, this can

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[70] At this point it is important to differentiate between classical (spatial) Bell inqualities (BI) and temporal Bell inequalities (TBI), i.e., Bell's theorem for temporal order (Paz & Mahler, 1993; Zych, Costa, Pikovski, & Brukner, 2017) This difference is directly related to the Heisenberg uncertainty principle (Heisenberg, 1927) which asserts a fundamental limit to the precision of measurements.
$\Delta x \Delta p \geq h/4\pi$, where h is Plancks constant.
Specifically, this principle describes a mathematical inequality which states that complementary variables (i.e., complementary physical properties such as position x and momentum p) cannot be simultaneously known (observed/measured) with an arbitrarily high degree of precision. It is important to emphasise that this principle is completely independent of the inaccuracy of the measurement device or any other experimental variables (e.g., noise, unknown experimental confounds, etc.). Rather, the uncertainty principle is fundamental to the nature of the quantum mechanical description of reality. The Heisenbergian uncertainty principle constitutes one of the defining difference between spatial and temporal Bell inequalities as the constraint does not apply when two measurements are performed at the same point in time on two different particles located in different space points. On the other hand, it does constraint the ability to resolve the two states in a second measurement at a later time on the same particle (Calarco, Cini, & Onofrio, 1999).

evoke strong emotional/affective responses and various cognitive defence mechanisms might be activated to protect our conceptual schemata from the radical (Bayesian) revision of beliefs which is necessary when these finding and their implications are taken seriously. The well-studied phenomenon of belief-bias is relevant in this regard. Belief-bias a phenomenon in the psychology of thinking and logical (syllogistic) reasoning which demonstrates that reasoning is biased by *a priori* beliefs, even though the logical argument might be syntactically valid (i.e., logically sound). This conflict between semantic believability (a System 1 process) and syntactical logical validity (a System 2 process) leads to large proportions of fallacious conclusions when these aspect are incongruent, viz., the conclusion of a given argument is logically valid but semantically unbelievable according to priors beliefs (J. St. B. T. Evans, Barston, & Pollard, 1983; Kahneman, 2003; Tsujii & Watanabe, 2009). A more detailed description of belief-bias can be found in Appendix A6. Hence, for proper scientific thinking it is important to counteract this systematic belief-bias in order to deduce logically valid conclusions.

There is general consensus[71] (i.e., a strong prior belief) in cognitive psychology and the neurosciences that cognitive processes are ultimately reducible to neuronal processes, a perspective which goes by the name of "materialistic reductionism" (however, this

[71] Group-consensus (conformity) is another important factor which can dramatically distort the validity of scientific judgments and reasoning (Asch, 1955). Social-identity theory (Tajfel & Turner, 1986) is yet another powerful explanatory theoretical framework in this respect. If the social identity of a given scientists (or a group of scientists, or a whole scientific discipline) is based on the (untested) assumption of local realism, then any evidence which challenges this shared Weltanschauung is perceived as a threat to the group norm. These group processes are in conflict with rational and "objective" scientific reasoning. These well-documented effects are based on complex social dynamics which cannot be ignored in the context of scientific reasoning. The "need to belong" (Baumeister & Leary, 1995) is a fundamental human motive which (implicitly) motivates much of human behaviour. Scientists (and the groups they affiliate with) are no exception. Awareness of these confounding effects on reasoning and decision-making is crucial but usually exclusively taught as part of a specialised social psychology curriculum, which is (dis)regarded as a "soft" science even though it uses the same quantitative methods) as other disciplines, e.g., the biomedical sciences (to be precise, a loically incoherent hybrid between Fisherian and Neyman-Pearsonian hypothesis testing, but see Gigerenzer, 1993).

conceptual paradigm is not based on empirical evidence – it is merely hypothetical). Therefore, the notion of realism (as used in physics) is an almost unquestioned assumption of all mainstream cognitive (and neurological) models. An interesting question is the following: If TBI is violated at the cognitive process level, but the brain is assumed to be classical, then what exactly is the substrate of the quantum process (Yearsley & Pothos, 2014)? And what role do quantum processes play in neurophysiology/neurochemistry (Baars & Edelman, 2012; Koch & Hepp, 2006)? Recently, several quantum models of the brain have been proposed. The most widely known (and most controversial) theory is the "Orchestrated objective reduction" (Orch-OR) hypothesis formulated by Sir Roger Penrose and Stuart Hameroff which postulates that quantum processes at the neuronal microtubular level are responsible for the emergence of consciousness. Appendix A2 provides a synopsis of the conjectural Orch-OR quantum-brain hypothesis.

1.9 A real-word example of superposition and collapse

The generic probability framework developed in quantum physics appears to be relevant to multifarious psychological processes (Atmanspacher & Römer, 2012). Especially, the concept of noncommutativity appears to be pertinent for cognitive operations. Noncommutativity, in turn, is closely related to superposition and the collapse of the wave-function. The following paragraph provides an intuitive simplistic illustration of the principle of superposition applied to a real-world decision-making scenario. Subsequently, we will discuss the concept in somewhat more technical terms in the context of visual perception.

Here is the real-world example in the context of academic decision-making: Suppose an examiner has to decide whether a Ph.D. thesis should be passed or failed. From a classical information processing point of view the response format is binary, i.e., either yes or no response (lets denote this with 1 or 0), a dichotomous decision. These values might change dynamically over time as the examiner reads the thesis, but at any moment in time, the associated cognitive variable is assumed to be in a definite fixed state (see Figure 8). However, contrary to the classical notion, it seems plausible that the examiners cognitive state does not jump from one discrete binary state to another (like a flip-flop or an electron jumping from one orbit to another). Instead, the examiner might experience ambiguity about both states simultaneously (see Figure 9). That is, until a final decision is made, the cognitive system is in a superpositional state, i.e., an indeterminate state. When the decision is finally reached (e.g., no corrections, i.e., 0), the superpositional 1/0 state instantly transforms into a determinate state. This is the simplified basic tenet of superposition and collapse in QP theory, explained in the form of an intuitive analogy.

Observe state i at time t where p_i = probability of state i

$p(t \mid i) = [1,0,..,1,..0]'$

$p(t + s) = T(s) \cdot p(t \mid i)$

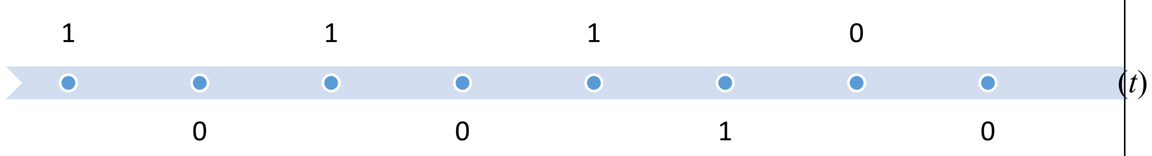

Figure 8. Classical sequential model (Markov).

Observe state i at time t where ψ_i = amplitude of state i

$\psi(t \mid i) = [1,0,..,1,..0]'$

$\psi(t + s) = U(s) \cdot \psi(t \mid i)$

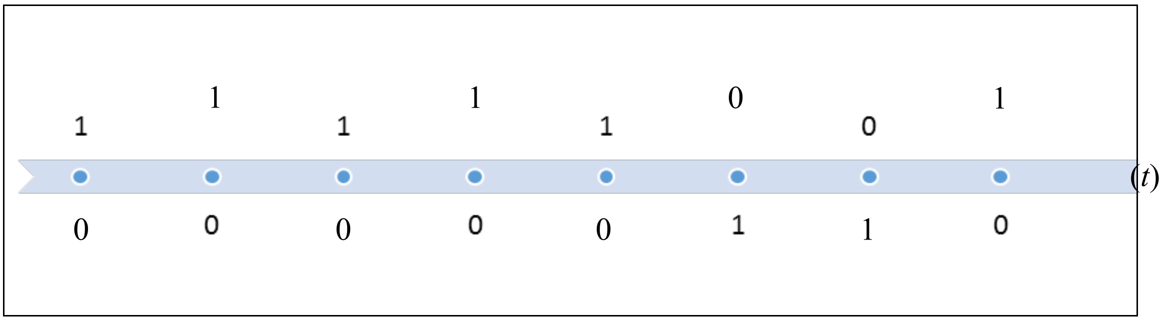

Figure 9. Quantum probability model (Schrödinger).

This example illustrates the concept of “quantum indeterminacy” (Busch, 1985; cf. Glick, 2017) which stands in direct contrast with deterministic physical theories which predate quantum physics. Deterministic theories assumed that:

1) a given (physical) system always has a in principle determinable state that is precisely defined by all its properties.
2) the state of the system is uniquely determined by the measurable properties of the system (i.e., the inverse of point 1).

Thus, an adequate account of quantum indeterminacy needs to operationalise what constitutes a measurement – an unresolved “hard” problem which we will address in greater detail in the general discussion section.

1.10 Determinism vs. constructivism

“The procedure of measurement has an essential influence on the conditions on which the very definition of the physical quantities in question rests.” (Bohr, 1935, p.1025).

According to the theoretical nexus of quantum cognition, superposition, noncommutativity, and complementarity are closely interlinked phenomena. To reiterate the basic principles of QP in more technical terms, superposition defines a state which has a specific amplitude across >1 possibilities. QP postulates that taking a measurement causes a continuously distributed state to collapse into a discontinuous discrete state (via wave function collapse as described by Schrödinger's wave-equation). That is, the quantity being measured changes from a superimposed state into an Eigenstate.[72] The crucial difference to sequential Markovian data models (e.g., Camastra & Vinciarelli, 2015) is the impossibility to create what Schrödinger called an "Erwartungskatalog" (expectation catalogue), i.e., an index of the trajectory of states of the system as a discrete time-series. Note that it is only when a measurement is taken that a discrete value is created via collapse of Ψ. The trajectory of the state of a quantum system is called a "quantum trajectory" (Sanz & Borondo, 2007) and can be conceptualised as stochastic random walk[73] in a multidimensional Hilbert space. However, in contrast to classical random walk models, the evolution of the quantum system is conditioned upon measurements. In the current context of perceptual judgments, we are particularly interested in the question whether the perceived luminance level of a visual stimulus changes depending on whether there was an antecedent psychophysical measurement or not. Let us assume that the perceptual evaluation is developing over two stages. Each stage entails the presentation of a visual stimulus (a grey rectangle with high or low luminance levels). From a classical probability (CP) perspective, it should not make any difference if the percipient is requested to provide a perceptual evaluation just after the second stage or after the first stage as well. If an intermediate evaluation is required, this is assumed to merely read-out an already pre-existing internal visual percept and therefore this should not have any impact on the final perceptual judgment in the second stage. By contrast, from QP perspective, a perceptual evaluation (an introspective measurement) can significantly

[72] The word "Eigenstate" is derived from the German word "Eigen", meaning "own", "inherent", or "characteristic".
[73] The term „random walk" was first introduced by the English mathematician and biostatistician Karl Pearson in a seminal NATURE article entitled „The Problem of the Random Walk" (Pearson, 1905).

change the state of the percipients' cognitive system (the cognitive state vector is realigned). Ergo, the intermittent perceptual judgment (i.e., cognitive measurement) can causally interfere with the result of the subsequent judgement. Note that the CP model does not predict any order effects due to an interjacent measurement whereas the QP model predicts such effects *a priori*. Of course, it is possible to explain such a finding in classical terms with auxiliary hypotheses (Leplin, 1982) which can be added *a posteriori* to the CP model in order to provide a *post hoc* explanation for this kind of carry-over effect. However, this can only be accomplished by adding additional components to the model which are not inherent to CP theory and which have not been predicted *a priori*. Consequently, according to the law of parsimony, i.e., Ockham's razor (Rodríguez-Fernández, 1999), the QP model should be preferred over the CP model.[74]

1.11 Quantum logic

The claim that logic should be subject to empirical research was first articulated by von Neumann and Birkhoff in the Annals of Mathematics (Birkhoff & Neumann, 1936). This position was later also advocated by Hilary Putnam (Cartwright, 2005; Maudlin, 2005). He argued that in the same way as non-Euclidean geometry revolutionised geometry, quantum mechanics changed the fundamental assumptions of logic. In his seminal paper entitled "Is logic empirical", Putnam proposed the abandonment of the algebraic principle of distributivity, a position which has been challenged on several

[74]Note that CP and QP theory are not necessarily mutually exclusive. Classical probability is a special case within the more general overarching (unifying) quantum probability framework.

grounds (Bacciagaluppi, 2009; Gardner, 1971). The distributivity principle has received great attention in the context of irrational reasoning (Hampton, 2013; Sozzo, 2015), for instance, in the context of the conjunction fallacy (e.g., the Linda paradox[75]). However, while violations of the distributivity principle are inconsistent with classical logic, they are entirely consistent in the axiomatic framework and various *prima vista* seemingly irrational reasoning fallacies have been successfully modelled using quantum logic (Moreira & Wichert, 2016b). A pivotal difference from classical Boolean algebra is described by the von Neumann's concept of "simultaneous decidability" and extension of simultaneous measurement. Birkhoff's and von Neumann's interpretation of quantum mechanics have been extensively discussed in philosophy of science, *inter alia*, by Karl Popper (Popper, 1968).

In the psychological literature, classical probability theory dominates all modelling efforts. That is, almost all cognitive and neuroscientific models implicitly assume the validity of classical probability theory. The standard model of probability (known as Boltzmann/Gibbs distribution in physics or Kolmogorov's laws in classical probability theory) is based on the set-theoretic assumption that probabilities always add up to 1. This is formally axiomatized in the law of conditional probability. The Kolmogorov formulation is as follows (Kolmogorov, 1956):

[75] A prototypical version of Linda paradox goes as follows (Tversky & Kahneman, 1983):
Linda is 31 years old, single, outspoken, and very bright. She majored in philosophy. As a student, she was deeply concerned with issues of discrimination and social justice, and also participated in anti-nuclear demonstrations.
Which is more probable?
  a) **Linda is a bank teller.**
  b) **Linda is a bank teller and is active in the feminist movement.**

(*We ask the reader to answer the question before reading the following paragraph*.)
The majority of respondent "irrationally" choose option b) over option a). However, the conjunction of both events occurring together is probabilistically less than or equal to either event occurring in isolation. This inequality can be formalised as $Pr(A \wedge B) \leq Pr(A)$ and $Pr(A \wedge B) \leq Pr(B)$.

Equation 5. Kolmogorov's probability axiom

$$P(A|B) = \frac{P(A \cap B)}{P(B)}$$

Current cognitive and decision models are almost exclusively derived from the Kolmogorov axioms (Kolmogorov, 1933/1950). Quantum probability is based on fundamentally different mathematical axioms and has the potential to provide a viable alternative to the dominant Kolmogorovian paradigm[76].

1.12 Noncommutative decisions: QQ-equality in sequential measurements

In the current experimental context, the most relevant difference between classical and quantum probability models is the way in which they deal with violations of the commutativity axiom (the quantum model allows for violations of symmetry, that is, observables do not have to commute). In other terms, the defining difference between classical probability theory and quantum probability theory is noncommutativity of operators.[77] If projectors do commute, classical probability theory applies, "iff" they do not commute, quantum probability applies. Accordingly, quantum theory is only applicable in cases of noncommutativity (Busemeyer & Bruza, 2012), otherwise it is identical to the classical probability framework. Quantum stochastic calculus is the

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[76] Bose-Einstein statistics are another counterintuitive instance of quantum probabilities which are incongruent with classical notions of probability (quantum dice). The details go beyond the scope of this chapter. However, for the curious reader, we created a website which contains additional information on this topic: http://irrational-decisions.com/quantum_dice/

[77] In matrix algebra, the product of matrices does not necessarily commute, for instance:

$$\begin{bmatrix} 0 & 2 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 & 1 \\ 0 & 1 \end{bmatrix} \neq \begin{bmatrix} 0 & 1 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 1 \end{bmatrix}$$

In matrix algebra, every subspace corresponds to a projector, i.e., the projector is an operator that takes a vector and projects it onto the subspace (Busemeyer & Bruza, 2012) and projector A multiplied by projector B does not always give the same result as projector B times projector A.

mathematical framework which is used to model the random[78] evolution of quantum systems undergoing measurements. It is a generalization of stochastic calculus to noncommuting observables (Hudson & Parthasarathy, 1984).

Equation 6. Classical probability theory axiom (commutative).

$$P(A \cap B) = P(B \cap A)$$

Equation 7. Quantum probability theory axiom (noncommutative).

$$||P_B P_A S^2|| \neq ||P_A P_B S^2||$$

How do we transfer this abstract mathematical formalism to actual real-world phenomena? Let us consider a representative realistic example: In a Gallup poll conducted in 1997, half of the sample (n = 1002) was asked, "Do you generally think Bill Clinton is honest and trustworthy?" and subsequently they were asked the same question about Al Gore (Moore, 2002). Using the standard (random) split sample technique, the other 50% of respondents answered exactly the same questions but the question order was reversed. When the question about Clinton was asked first, he received a 53% agreement whereas Gore received 76% (Δ 23%). However, when the

[78] Werner Heisenberg differentiates between objective randomness and subjective randomness. While the outcome of throwing two die is subjectively random, quantum randomness is objectively random. In principle, the ooutcome of throwing a die could be determined – however the Newtonian dynmics are just to complex (viz., Laplace's omniscient demon could in principle predict the outcome). Quantum randomness is by its very nature indeterminstic and therefore not dependent on the epistemological state of the observer (e.g., unknown hidden variables). To twist Einsteins famous words: God does play quantum dice, i.e., at its most fundamental level nature is indeterministic. This empirical fact poses a serious problem for mechanistic causal models across the sciences. Specifically, because the demarcation criterion between "quantum vs. not quantum" (i.e., micro vs. macro) appers to be arbitry (Arndt et al., 1999; Van der Wal et al., 2000). That is quantum effects are observed in macro scale molecules and eminent physicists argue that there is theoretically no upper limit to the size of object which obey quantum laws (Zeilinger, 2012).

question order (the order of sequential measurements) was inverted Clinton received 59% while Gore received only 67% (Δ 8%).

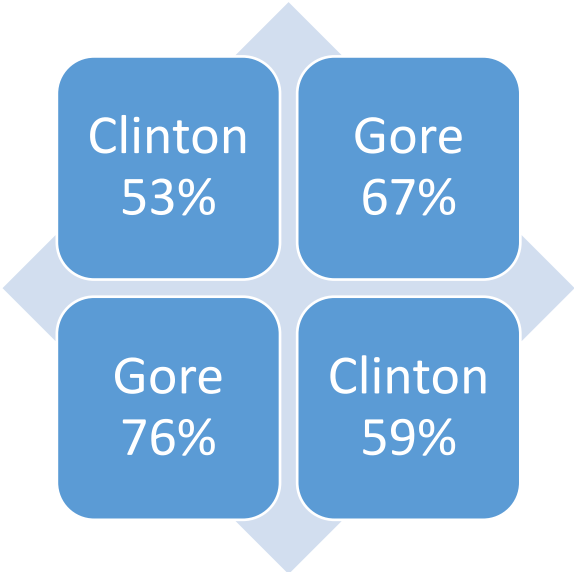

Figure 10. Noncommutativity in attitudinal decisions.

Classical probability theory cannot account for this kind of order effects because events are represented as sets and are stipulated to be commutative, that is, $P(A \cap B) = P(B \cap A)$. That is, the empirically observed order-effects clearly violate the Kolmogorovian commutativity axiom. Quantum models of cognition can account for these *prima facie* "irrational" judgment and decision-making phenomena and indeed predict them *a priori*. In the pertinent literature, the effect of posing attitude questions successively in different orders has been termed QQ-equality, i.e., quantum question equality (Z. Wang, Solloway, Shiffrin, & Busemeyer, 2014). This measurement effect has been investigated in a large scale meta-analytic study (based on 70 national representative surveys each containing between 600-3000 participants). The results provided strong support for the predicted QQ equality. Similar results in support of the broad applicability of QQ-equality to cognitive processes have been obtained in various unrelated domains, for instance, in dynamic semantics (beim Graben, 2013), thereby supporting the generalisability of QQ-equality across multiple domains of inquiry.[79] Taken together, these findings suggest that QP, originally developed to explain noncommutativity of measurements in quantum physics, provides a desirably parsimonious explanation for measurement order effects in the social, behavioural, and cognitive sciences (Z. Wang & Busemeyer, 2013). Classical Bayesian[80] and Markov models are unable to account for QQ-equality and are thus incapable of explaining the empirical data. In the quantum probability framework events are subspaces in an *n* dimensional Hilbert space and they may either be compatible or incompatible (incompatible events are aligned orthogonal in respect to each other). In other words, noncommutative order effects can be modelled in terms of incompatible projectors on a Hilbert space (Z. Wang et al., 2014). If they are compatible, they can simultaneously coexist without influencing each other. On the other hand, incompatible event, as illustrated in the example above, interfere with each other, thereby causing order interference effects. In quantum physics, these interference effects have been studied extensively and the constructive role of measurements/observations is firmly established even though the exact nature of what exactly defines a measurement/observation is a wide-open question and is related to the measurement problem (Echenique-Robba, 2013). Several theorist argue that consciousness is crucial for the collapse of the wave-

[79] QQ-equality was initially developed to account for noncommutativity of measurements in quantum physics. However, multiple studies have demonstrated that the same principle is applicable to various psychological processes. This can be regarded as a paradigmatic case of "scientific consilience" (E. O. Wilson, 1998b), viz., evidence from unrelated sources support the same scientific theory. In other words, converging evidence corroborates the generalisability of QQ-equality across multiple domains. QQ-equality can be formalised as follows:

$$q = [p(\mathrm{AyBy}) + p(\mathrm{AnBn})] - [p(\mathrm{ByAy}) + p(\mathrm{BnAn})]$$
$$= [p(\mathrm{AyBn}) + p(\mathrm{AnBy})] - [p(\mathrm{ByAn}) + p(\mathrm{BnAy})] = 0.$$

For mathematical details see the supplemental material provided by Wang et al., (2014) or the textbook by Busemeyer & Bruza (2012).

[80] Several lines of research combine Bayesian approaches with quantum logic. Combinatorial approaches include the "Quantum Bayes Rule" (Schack, Brun, & Caves, 2001) and "Quantum Bayesian Networks" (Low et al., 2014). Recently, "quantum-like Bayesian networks" have been utilised to model decision making processes (Moreira & Wichert, 2016a) and it has been demonstrated that they are able to parsimoniously accommodate violations of the laws of classical probability, for instance, the comonotonic "sure-thing principle" (A. Y. Khrennikov & Haven, 2009).

function, thereby assigning consciousness a crucial role within the formal framework of quantum physics (that is, localisable matter only exists when observed by a conscious agent) (C. U. M. Smith, 2009).

In the context of the Gallup poll example described before, the quantum-like constructive role of measurements can be described as follows: The cognitive state constructed from the first question changes the cognitive context used for evaluating the second question, i.e., the cognitive state vector is rotated, and a subsequent judgment is based on this change in cognitive state. From a quantum cognition perspective, attitudes are not simply retrieved from memory structures – they are constructed online or "on the fly" (White et al., 2014b).

The quantum cognition approach can be regarded as a form of cognitive constructivism, not to be confused with Vygotskian or Piagetian constructivism, although there are significant conceptual similarities, i.e., the view of the cogniser as an *active* (rather than passive) information processor and the emphasise on the *contextual situatedness* of information processing (Barrouillet, 2015; Gerstenmaier & Mandl, 2001)).

In the cognitive sciences, the assumption that cognitive variables have a fixed value at each moment in time is generally unquestioned and has hitherto been uncontroversial. Cognitive variables might change diachronically (as a function of t) but at each specific point in time the cognitive system is assumed to be in a definite state. This intuitions appears to be common sense, however, scientific facts and our intuitions about reality do not always coincide. An alternative way to look at cognitive variables is that measuring cognitive variables is a constructive process which actively creates the specific state of the variable under investigation. This implies that it is impossible to create an index of the possible values of the cognitive variables at each and every point in time (Yearsley & Pothos, 2014).

This notion is indirectly supported by recent neuroscientific simulation studies, which focus on the energy dynamics of neural network structures (Sporns, 2014). From an evolutionary and cognitive economy point of view, it seems to be very inefficient to store a vast number of opinions about reality in our neuronal networks (e.g., sparse coding of memory). Santiago Ramón y Cajal postulated over 100 years ago that our neuronal morphology is shaped by "laws of conservation for time, space, and material" (Cajal, 1895). Following this quasi-Helmholtzian line of thought, it seems plausible that most of our opinions are constructed in real time[81] and do not exist *a priori* in a determinate state in some (neural) substrate. The contextual constructivism postulated by quantum cognition provides an elegant framework to formalize this intuition (Busemeyer & Bruza, 2013).

1.13 Quantum models of cognitive processes

Recent findings in quantum cognition have challenged many of the most fundamental assumptions about the basic characteristics of cognitive systems and they have led to the development of a number of novel modelling approaches (Busemeyer & Bruza, 2012). Quantum cognition introduces several completely new concepts to the field of psychology which were previously not part of the scientific discourse within the discipline. These novel concepts are superposition, entanglement, and incompatibility, to name just the most important innovations. These novel concepts have provided fresh insights into the nature of various cognitive processes (Aerts & Sassoli de Bianchi, 2015; Bruza, Busemeyer, & Gabora, 2009; Busemeyer, Pothos, Franco, & Trueblood,

[81] It should be noted that answers to certain classes of questions are very likely retrieved from relatively stable memory (network) structures rather than being contextually constructed (e.g., autobiographical information).

2011a; Conte, Khrennikov, Todarello, Federici, & Zbilut, 2009; Segalowitz, 2009; Sozzo, 2015; Z. Wang et al., 2013).

1.14 Contextualism, borderline vagueness, and Sôritês paradox

One of the most widely cited arguments that motivates the application of QP to cognitive phenomena is the existence of interference effects in higher-order cognitive processes such as decision making and logical reasoning (Aerts, 2009; Blutner, Pothos, & Bruza, 2013; Busemeyer, Wang, & Lambert-Mogiliansky, 2009). A recent publication entitled "a quantum probability perspective on borderline vagueness" (Blutner et al., 2013) discusses the importance of the concept of noncommutativity in the context of decisions involving natural concepts. Natural concepts oftentimes lack precisely defined extensions, for instance, what is the smallest size of a man called "tall"? The demarcating criterion which differentiates between "tall" and "not tall" is not clearly defined (Karl Popper struggled with the same "demarcation problem" in the context of science versus pseudo-science). The authors investigated the fuzziness of natural everyday concepts and compare various approaches (e.g., fuzzy logic). We argue that similar to semantic concepts, visual categorisation is oftentimes ambiguous and vague. Specifically, we argue that the fuzzy boundaries of natural concepts described in other quantum cognition models are particularly applicable to visual judgments. For instance, what is the lowest luminance level of a stimulus categorised as "bright"? The absence of a modulus or "perceptual anchor" complicates the matter even further. As with natural concepts, the demarcating boundaries between "bright" and "not bright" are not clearly defined and it is often uncertain if the predicate applies to a given visual stimulus (partly due to the imprecise definition of the predicate). It follows that Sôritês paradox (also known as "the problem of the heap") is extendable to visual perception (and perception in general) especially in the context of the "just noticeable difference", JND (Norwich & Wong, 1997). Sôritês paradox (which has been ascribed to the Greek philosopher Eubulides of Miletus) illustrates the vagueness of predicates (Blutner et al., 2013). The paradox is based on the seemingly simple question: When does a heap of sand become a heap?[82] The associated syllogistic argument can be formulated as follows:

1st premise:	100000000000 grains of sand are a heap of sand.
2nd premise:	A heap of sand minus one grain is still a heap.
∴ Conclusion:	Ergo, a single grain of sand is a heap.

Sôritês paradox as a syllogistic argument, i.e., *modus ponens* $(P \rightarrow Q) \wedge P) \rightarrow Q$).

Repeated application of the minor premise (iterative removal of single grains of sand, i.e., inferential "forward chaining") leads to the paradoxical, but deductively necessary (i.e., logically valid) conclusion that a single grain of sand is a heap. Figure 11 illustrates Sôritês paradox applied to visual perception. Adjacent luminance differences (e.g., tick-mark 1 versus 2) are indistinguishable by the human visual system while larger contrasts (e.g., tick mark 2 versus 3) are easily distinguishable.

[82]The "Bald Man (*phalakros*) paradox" is another allegory which illustrates the vagueness of predicates: A amn with a full head of hair is not bald. The removal of a single hair will not turn him into a bold man. However, diachronically, continuous repeated removal of single hairs will necessarily result in baldness.

Figure 11. Sôritês paradox in visual brightness perception.

Conceptual vagueness has received a lot of attention from logicians, philosophers, and psychologists (e.g., Eklund, 2011; Putnam, 1983; Serchuk, Hargreaves, & Zach, 2011). Here we are particularly concerned with cases of borderline contradictions such as “X is bright and not bright” where X denotes a borderline case (Blutner et al., 2013). Specifically, the “superposition” of “bright” and “not bright” is relevant from a quantum cognition perspective and it has been cogently argued in various psychological contexts that this kind of superposition introduces cognitive interference effects (Aerts, 2009; Aerts et al., 2011; Blutner et al., 2013). The postulated interference effects are analogous to those observed in quantum mechanics (i.e., the principle of superposition). The mathematical similarities have been discussed elsewhere (e.g., Busemeyer et al., 2011a) and go beyond the scope of this chapter.

Importantly for the experimental context at hand is the fact that the concept “bright” is a vague concept because the exact demarcation from “not bright” is arbitrary and imprecise. When making perceptual judgments on a scale[83] ranging from “bright” to “not bright”, the percipient is confronted with a large degree of indeterminacy (especially when no absolute modulus is provided to anchor the judgment on the scale). It has been convincingly argued that the logical principle of non-contradiction (i.e., the semantic principle of bivalence[84]) does not necessarily hold true in such situations (Blutner et al., 2013). Epistemological accounts of vagueness (Sorensen, 1991; Wright, 1995) consider vagueness as the consequence of nescience on part of the percipient and

[83] For instance, as measured on a quasi-continuous psychophycial visual-analogue scale (Aitken, 1969).

[84] The semantic principle (or law) of bivalence is closely related to the 3rd Aristotelian law of thought, i.e., the law of the excluded middle (*principium tertii exclusi*) which can be stated in symbolic notation as $\vdash .p \equiv\sim (\sim p)$, where ~ signifies negation (after Whitehead & Russell, 1910). We will discuss this logical principle in greater detail in the context of quantum cognition in subsequent chapters because it plays a crucial role for superpositional states (quantum logic).

not a fundamentally ontological problem (but see Daniliuc & Daniliuc, 2004). Ontological accounts (e.g., contextualism), on the other hand, regard vagueness as a case of context-sensitivity (Åkerman & Greenough, 2010; Greenough, 2003; S. Shapiro & Greenough, 2005), i.e., the uncertainty associated with vagueness is regarded as a contextual phenomenon. This kind of context-dependence has been designated as "*v*-standards" and it describes any contextual parameter that is responsible for the vagueness (Åkerman & Greenough, 2010; Blutner et al., 2013). Fuzzy set theorists would agree with this ontological stance. They propose a form of logic which allows for graded truth values (L. a. Zadeh, 1965; L. A. Zadeh, 2008). Alxatib & Pelletier (2011) concluded that such borderline cases pose a serious problem for classical (Kolmogorovian/Boolean) logic. However, Blutner et al., (2013) demonstrated that QP provides a powerful explanatory framework for borderline contradictions (Blutner et al., 2013). QP utilises vectors in a Hilbert space $\mathcal{H}$ and it defines a linear operator on $\mathcal{H}$. Specifically, a projection operator[85] is a linear operator which projects vectors to certain subspaces of $\mathcal{H}$[86] . The underlying algebraic logic is non-Boolean in nature. Rather, it obeys the logic of orthoalgebra (Dalla Chiara & Giuntini, 1995). A defining difference between orthoalgebra and Boolean algebra is that the former does not obey the distributive law which form the basis of the law of total probability. The law of total probability, in turn, form the axiomatic basis for Bayes' rule (Bayes & Price, 1763). Ergo, QP is incompatible with Bayes' rule. Crucially, in QP the order in which

[85] Most psychologists are familiar with the General Linear Model and specifically multiple regression. The squared length of the projection in quantum probability theory is equivalent to the R^2 in multiple regression analysis, i.e., the coefficient of multiple determination (Busemeyer & Bruza, 2012).
[86] If a given system is in state Ψ, then a measurement will change the state of the system into a state which is an eigenvector *e* of *A* and the observed value λ will be the corresponding eigenvalue of the equation $A\ e = \lambda\ e$. This description implies that measurements are generally non-deterministic. The formulaic description for computing the associated probability distribution Pr on the possible outcomes given the initial state of the system Ψ is as follows: $\Pr(\lambda) = \langle \mathrm{E}(\lambda)\psi \mid \psi \rangle$, where E(λ) signifies the projection onto the space of eigenvectors of *A* with eigenvalue λ.

projection operators are combined can make a significant difference (Pothos & Busemeyer, 2013). Two projection operators A and B in a given Hilbert space $\mathcal{H}$ do not necessarily have to commute. That is, QP allows for $AB \neq BA$ (Blutner et al., 2013). However, if all projection operator commute, QP is equivalent to Boolean algebra. Thus, Boolean algebra is a special case of quantum probability theory which provides an overarching (more generalisable) axiomatic framework. We would like to emphasize the difference as it is crucial for the experimental investigation at hand: The principle of commutativity (or the violation thereof) is a critical criterion to differentiate between Boolean logic and quantum logic. We will discuss this noncommutativity criteria in greater detail in the context of constructive measurements of psychological observables. In QP notation, the term $\partial(A,B)$ is called the interference term. If $\partial(A,B)$ is zero, A and B commute (Blutner et al., 2013) otherwise A and B are non-Abelian[87]. In the context of psychological borderline vagueness (Alxatib & Pelletier, 2011), which is notoriously difficult to explain in a classical probability framework, it has been demonstrated that the QP model provides a parsimonious explanatory model with an acceptable/good index of fit, $\chi_2(4)=5.47$; $p=0.24$ (Blutner et al., 2013).

QP requires us to broaden and revise our conception of probability theory. QP is a much more general axiomatic framework compared to classical probability theory because it is able to describes all real-world properties (both at the micro and macro level). Some hardliners argue that reality as a whole is quantum mechanical, i.e., the world (and the whole universe) are a quantum system and that the underlying logical structure is based on the axioms of quantum logic. However, every-day reality appears classical (i.e.,

[87] In group theory, Abelian groups denote a group in which the application of a group operation to two group elements is independent on the order in which the operation is performed (viz a commutative group). In other terms, Abelian Groups (eponymously named after the mathematician Niels Hendrik Abel) conform to the commutativity axiom in abstract algebra (Durbin, 1967).

Boolean/Kolmogorovian) to the naïve percipient, but this is only the case because humans happened to almost exclusively perceive commuting observables (unless one discovers quantum mechanics or tests psychophysical commutativity in controlled empirical experiments). This naturally reinforces the "representativeness heuristic" which has been extensively studied in the field of thinking and reasoning (Kahneman & Tversky, 1972). In other words, numerous empirical encounters with commuting variables shaped and moulded our representations, heuristics, and intuitions and created the impression that commutativity is a constant nomological property of psychological (and physical) observables. However, from a rationalist point of view, insights derived from quantum mechanics require us to revise our most fundamental concepts of logic and the associated mathematical models. This empiricist position was also advocated by Quine, i.e., Quine argued that logic and mathematics are also subject to revision in the light of novel experiences and he explicitly employed "deviant quantum logic" as an example. In other words, Quine adopted initially an empirical quasi-Bayesian updating approach to logic. However, Quine later changed his opinion on this topic and argued that the revision of logic would be to essentially "change the subject". Hilary Putnam also participated in this fundamental debate about the empirical status of logic and he argued that we *are* indeed living in a quantum world in which quantum logic is applicable (R Rorty, 2005). In the same way as non-Euclidian space is a reality (which does not mean that Euclidian geometry is wrong – it just incomplete) quantum logic is a reality with tangible real-world consequences (e.g., Qubits in quantum computation, logic gates according to von Neumann's quantum logic, entanglement in quantum encryption, superposition in macro-molecules like C60/"Bucky balls", quantum chemistry, quantum biology, quantum cognition, etc. pp.). However, psychological factors like "the need for closure" might prevent individuals with certain personality propensities to adopt quantum logic. For instance, the personality trait "openness to experience" (McCrae, 1987) might be significantly correlated with a propensity to seek deeper information about the nature of reality, even in the light of seemingly paradoxical data which might put a "conscientious" personality type at unease (McCrae & Costa, 1997). We argue that quantum logic requires a great deal of divergent thinking and that it is negatively correlated with personality trait "need for closure". Moreover, the evolutionary predisposition to rely on habitual mechanisms of thought (cf. dual-process theory) prevents deeper cognitive reflection on the fundamental nature of basic cognitive concepts like the 3rd Aristotelian law of thought (which negates vagueness and multimodal logic). Likewise, existential phobias like *metathesiophobia* (fear of change) and *kainophobia* (fear of novelty) are important psychological concepts which are related to epistemological curiosity. The mere presentation of empirical facts is not enough to change scientific attitudes, especially when these facts dictate a revision of logic. Extralogical psychological factors need to be carefully considered because scientists are human beings which are prone to fallacious reasoning and selectivity biases, that is, various systematic errors of thinking an reasoning which lead to irrational decisions.

Based on this theoretical and empirical background, we argue that quantum cognition is an important predictive framework for the vagueness associated with psychophysical stimuli as the exact predication of perceptual instances is frequently objectively undecidable. Bayesian decision theory and other probabilistic statistical frameworks (e.g., empirical ranking theory) have been extensively applied to perceptual processes (e.g., Yang & Purves, 2004). However, besides in the context of ambiguous bistable stimuli, quantum probability theory has not been systematically tested in the context of psychophysics. The current thesis provides empirical evidence for the applicability of several QP principles to perceptual processes. Specifically, we tested several QP prediction in the domain of visual and auditory perception. We were particularly interested in violations of the commutativity axiom and constructive effects of introspective perceptual measurements.

1.15 Quantum-like constructivism in attitudinal and emotional judgements

Quantum-like constructive effects (White et al., 2015) have recently been published in a special issue of the Philosophical Transaction of the Royal Society (Haven & Khrennikov, 2015) which was dedicated to the emerging topic of quantum probability[88]. This line of research demonstrated experimentally that judgments about the trustworthiness of prominent political figures are constructive in nature, i.e., an initial judgment constructed an attitudinal state which statistically significantly influenced subsequent judgments. Specifically, the researchers addressed "the influence of an intermediate evaluation on judgements of celebrity trustworthiness" (White et al., 2015, p. 9). In a pilot study, the researchers collected "celebrity trustworthiness ratings" for a series of celebrities. Based on this piloted dataset, the research then designed the actual study which addressed the research question. They constructed pairs of celebrities with opposing trustworthiness ratings (stimulus valence: trustworthy/positive vs. untrustworthy/negative). These pairs were constructed in such a way that each pair contained a negative (N) and positive (P) valanced stimulus. For instance, a pair of stimuli in the NP (negative → positive) condition would consist of a picture of Yoko Ono (N) which was followed by John Lennon (P). In the pilot study, Yoko Ono was

[88] URL of the "Philosophical Transactions of the Royal Society A" special issue on quantum cognition: http://rsta.royalsocietypublishing.org/content/374/2058

rated as less trustworthy than John Lennon. In a second stimulus pair the presentation order was reversed (John Lennon was shown first followed by Yoko Ono), an example of an instance in the PN (positive → negative) condition. A 2 x 2 within-subjects factorial design with two independent variables was employed: "order of celebrity trustworthiness" (PN vs. NP) and "rating condition" (single vs. double). In each experimental condition participants were presented with a set of stimuli and were either requested to rate both (double rating condition) or merely the second stimulus (single rating condition). Experimental trials were divided into two blocks which both contained the same stimulus pairs (trial order within each block was randomized within participants). The crucial difference between blocks were the rating requirements. That is, participants rated each pair of stimuli twice, once under single rating instructions and once under double-rating instructions. Paired samples *t*-tests indicated significant difference between rating conditions. In the PN condition, the second stimuli were on average rated less trustworthy in the single rating condition compared to the double rating condition ($M = 4.36$, $SD = 0.98$ vs. $M = 4.54$, $SD = 0.94$; $t(51) = -2.23$, $p = 0.029$; $d = 0.3$). By contrast, in the NP condition this effect was reversed. The second stimuli was rated more trustworthy in the single rating condition compared to the double rating condition ($M = 6.02$, $SD = 0.90$ vs. $M = 5.85$, $SD = 1.05$; $t(51) = 2.23$, $p = 0.029$; $d = 0.3$). That is, the constructive role of the intermediate ratings statistically significantly increased the difference between stimuli. In sum, the results indicate that when a positively valanced stimulus (i.e., a more trustworthy celebrity) was rated first, the subsequent rating for a negatively valanced stimulus (i.e., a less trustworthy celebrity) was lower as compared to the single rating condition. *Vice versa*, when a negatively valanced stimulus (i.e., a less trustworthy celebrity) was rated first, the rating of the second more positively valanced stimulus (i.e., a more trustworthy celebrity) was higher as compared to the single rating condition. This pattern of result provides a direct replication of a previous study described earlier (White et al., 2014b) which focused on affective (emotional) evaluations instead of trustworthiness ratings. The pattern of results of both studies is contrasted in Figure 12 and Figure 13. In addition, we reanalysed the results of (White et al., 2014b) in a Bayesian framework. The resulting Bayes Factors and their interpretation can be found in Appendix A9.

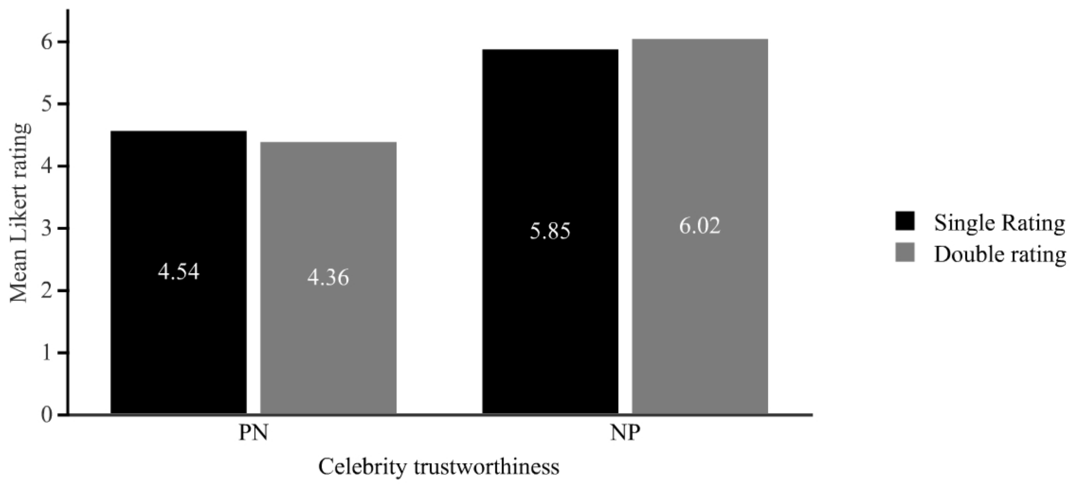

Figure 12. Trustworthiness ratings as a function of experimental condition (White et al., 2015).

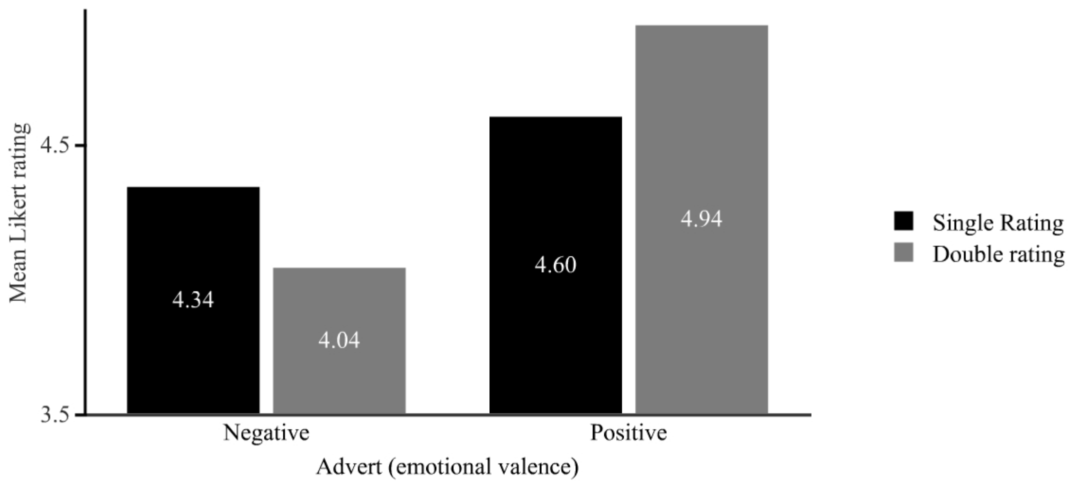

Figure 13. Emotional valence as a function of experimental condition (White et al., 2014b).

White et al., (2014, 2015) argued that a model based on the axiomatic principles of QP provides a viable and parsimonious, yet powerful explanation for these empirical results. In quantum mechanics, it is a firmly established principle that the mere act of taking a measurement changes the state of the system under investigation. The act of taking a measurement is assumed to collapse Ψ, thereby converting and indeterminate stochastic state (described by Schrödinger's wave-function) into a discrete and precisely determinable state. That is, the measurement constructs the state of the system due to the collapse of the wave-function. In the context of cognitive processes, this means that every judgment and decision can be regarded as an introspective measurement which constructs the cognitive state (i.e., the state of the system under investigation) "on the fly". This change in the cognitive state (caused by a constructive introspective measurement) has influences on subsequent measurements. This notion is clearly opposed to classical (Markov) models which assume that the system is always in a discrete state and that measurement (introspection) merely "reads out" an already pre-existing state. Thus, the quantum perspective assumes that states are constructed whereas the classical approach assumes that measurement are objective representations of pre-existing states. In this context, the importance of stimulus-incompatibility should be underscored. Stimulus-incompatibility is necessary criterion for the applicability of the quantum probability framework to physical and psychological observables. Incompatibility gives rise to the “no information without disturbance” maxim (Heinosaari, Miyadera, & Ziman, 2015) and it is crucial factor for the emergence of noncommutativity effects.

Taken together, the discussed experiments provide corroborating evidence for the validity of the quantum cognition framework in respect to attitudinal and emotional judgments.

Specifically, the results corroborate the importance of the quantum mechanical noncommutativity principle. As discussed in the preceding paragraphs, a fundamental difference between classical (Boolean) observables and quantum mechanical observables is the dependence of sequential measurement outcomes on the specific order in which measurements of quantum mechanical observables are performed. Observables corresponding to noncommutative operators are called incompatible and his asymmetrical inequality can be symbolically expresses as follows: $\mathrm{AB} - \mathrm{BA} \neq 0$. The goal of our experimentation was to investigate this effect in the domain of perceptual processes, i.e., in a rigorously controlled reductionistic psychophysics framework. This approach has several advantages of the experiments conducted by White et al., (2015, 2016). From a methodological point of view, visual stimuli can be experimentally controlled in a much more precise way than, for instance, attitudinal or emotional judgments, thereby reducing between-subject reliability. Furthermore, from a phylogenetic perspective, the visual system is a much more basic system than the emotional system and its anatomical and functional characteristics are shared with many non-human species. If noncommutativity applies to human perception, one might predict that it can also be observed in non-human species (e.g., primates, rodents, etc.). In addition, our scientific knowledge of the visual system is much more sophisticated compared to higher-order cognitive processes which are much more elusive. Therefore, a reductionist approach would try to demonstrate noncommutativity at the lowest level possible in order to establish a firm empirical foundation. Subsequently, the generalisability of the phenomenon should be tested in more complex cognitive situations. Our experimental approach can thus be regarded as an attempt to establish noncommutativity in low-level perceptual processes in order to establish a psychophysical foundation.

1.16 Current empirical research

The main question that motivated the present investigations is the following: What exactly happens when people make perceptual decisions under conditions of uncertainty? We were particularly interested in sequential noncommutativity effects and the constructive role of introspective psychophysical measurements. Our theorising was motivated by various psychophysical theories of complementarity (J. C. Baird, 1997). Specifically, we wanted to investigate if the mere act of taking a psychophysical measurement *per se* constructs the perceptual process in question. Random walk models (e.g., Ratcliff & Smith, 2004; Usher & McClelland, 2001) which focus on reaction times in various decision scenarios assume that evidence (information) is accumulated over time until a specific decision-threshold is reached (cf. Harris, Waddington, Biscione, & Manzi, 2014). In this class of “rise-to-threshold models”, the weight associated with each option increases chronologically in a progressive manner.

However, at each discrete point in the temporal sequence the system is assumed to be in a definite determinate state. This state can in principle be accessed by taking a measurement. Moreover, it is assumed that the act of measuring does not influence the state under investigation.
That is, classical models presuppose that a given system is consistently in a specific state, even though the observers' cognition of this state might be uncertain (e.g., a hidden variable). This appears to be a very logical postulate. How else could one build a model of a system if it is not in a definite (stable) and objectively measurable state at any point in time?

However, this mainly unquestioned assumption stands in sharp contrast with one of the main ideas of quantum probability (QP) which provides the axiomatic basis of quantum theory. A fundamental insight derived from quantum theory is that taking a "physical measurement" of a "physical system" actively creates rather than passively records the property under investigation.[89] By contrast, classical theories assume that taking a measurement merely reads out an already pre-existing state of a system. Moreover, QP is incompatible with the classical notion that a given system (be it physical or psychological) is always in a determinable state at any point in time. By contrast, QP allows for the possibility that a system can be in a superpositional state in which *n* possibilities can exist simultaneously. It is only when a measurement is taken that these undetermined potentialities collapse into determinate actualities. In our experiment, we tested various hypotheses which were a priori derived from the quantum probability framework. We were particularly interested in noncommutativity in perceptual

[89] In the context of decision-making, quantum cognition replaces the term "physical measurement" with "human decision" and "physical system" with "cognitive system".

processes and the constructive role of psychophysical measurements. Our predictions are compatible with the results of previous research which investigated the same phenomena in emotional and attitudinal judgments (White et al., 2015, 2014b).

CHAPTER 2. EXPERIMENT #1: NONCOMMUTATIVITY IN SEQUENTIAL VISUAL PERCEPTUAL JUDGMENTS

2.1 Experimental purpose

The primary objective of this experiment was to investigate noncommutativity in sequential psychophysical measurements from a QP perspective, as has been previously proposed by Atmanspacher & Römer (Atmanspacher & Römer, 2012), *inter alia*. QP makes *a priori* and parameter-free predictions about sequential order effects (Z. Wang et al., 2014). Specifically, our hypotheses were logically derived from the QQ-equality principle (Z. Wang et al., 2014) discussed in the introduction. Thus, the present experiment can be regarded as a translation of empirical findings from the affective/emotional domain to the psychophysical domain.

Another interesting aspect which connects our research with previous pertinent experiments (i.e., White et al., 2015, 2014b) is based on various embodied cognition hypotheses concerning the affective properties of psychophysical stimuli. For instance, it has been demonstrated that brightness is associated with positive emotional valence and affect (B. P. Meier, Robinson, & Clore, 2004). Furthermore, virtuous attributes like trustworthiness, morality, and ethical behaviour have been repeatedly linked to brightness (e.g., Chiou & Cheng, 2013). From a cognitive linguistics point of view (especially in the framework of conceptual metaphor theory (Lakoff, 1993; Lakoff & Johnson, 1980)), the psychophysical stimuli we utilised can thus be regarded as conceptually related to the stimuli which were utilised in related research (White et al., 2015, 2014b). Specifically, stimulus brightness is conceptually closely associated with cognitive representations of trustworthiness and positive affect (B. P. Meier, Robinson, Crawford, & Ahlvers, 2007). That is, the neuronal sensorimotor grounding of affective cognitive states (an abstract "intangible" concept) is based on concrete perceptual properties (i.e., visual, tactile, auditory, olfactory, etc.). The nonconcrete concept (affect) is mapped on the concrete domain (e.g., via Hebbian learning/synaptic long-term potentiation).[90] For instance, it has been experimentally demonstrated that brightness differences influence the evaluation of affective pictures (Lakens, Fockenberg, Lemmens, Ham, & Midden, 2013), a research finding which emphasises the general conceptual relation between more basic sensorimotor experiences (in the Piagetian sense) and higher-order cognitive/affective constructs like attitudes and affect (Dael, Perseguers, Marchand, Antonietti, & Mohr, 2016). Therefore, our experiment can be interpreted from an embodied cognition point of view (Kurt, Eroğlu, Bayram Kuzgun, & Güntekin, 2017). Specifically, brightness can be regarded as a source domain and trustworthiness as the target domain. That is, the psychophysical domain is more primary and provides the sensorimotor "primitives" (primary metaphors) for more complex higher-order cognitive constructs (e.g., affect). However, for reasons of parsimony and focus, a more detailed discussion of the associated cognitive representations (embodied image schemata (Lakoff, 1987, 1993, 1994)) goes beyond the scope of this chapter. For now, it is sufficient to note that "brightness" and "affect" are neuronally and conceptually closely interlinked from an embodied cognition point of view (Lakoff & Johnson, 1980; Lakoff & Nuñez, 2000). From a neuroscientific point of view, there is thus significant neuronal overlap between the neural correlates of representations of brightness and affect. ´Based on this theoretical background one might therefore predict that noncommutativity effects observed in higher-order concepts

[90] A more detailed description of embodied cognition and conceptual metaphor theory can be found inAppendix B1. In the context of the current investigation, the representational association between brightness perception and attitudinal/affective judgments (White et al., 2015, 2014b) is of particular theoretical interest. We an overview of pertinent studies to undergird this claim.

like affect and trustworthiness (White et al., 2015, 2014b) generalise to the associated embodiments of the concept, i.e., brightness perception.

In order to test our hypotheses, we utilised various parametric and non-parametric inferential statistical testing procedures. This was done in order to increase the robustness of our analyses and consequently the resulting logical inferences which are based on these calculations. Moreover, statistics is currently in a process of reformation (Cowles, 2014), especially in psychology, neuroscience, and the bio-medical sciences. The "new statistics" are replacing the conventional Fisherian methods with more "sophisticated" inferential techniques (Cumming, 2012, 2013, 2014; Eich, 2014).[91] In the subsequent analyses, we utilised the most promising novel methodologies and compared the results. By doing so we followed recent recommendation by the APA journal "Psychological Science" which recently announced changes to its publication guidelines. That is, we constructed confidence intervals and calculated effect-sizes for all parameters of interest. Moreover, we went one step further and constructed confidence interval for the effect sizes. In addition, we utilised the Vovk-Sellke maximum *p*-ratio (VS-MPR) to convert conventional *p*-values into a more readily interpretable format that is less prone to logical fallacies (Sellke, Bayarri, & Berger, 2001; Vovk, 1993). Furthermore, we applied bootstrapping techniques in order to check the robustness of our results and to maximise inferential power. We obtained bootstrapped confidence intervals for all parameters of interest. In addition, we conducted our analyses in two complementary Bayesian frameworks in order to cross-

[91] The suggested alternatives are mainly confidence intervals and effect sizes. However, these recommendation do not address the crux of the problem, i.e., the logically inconsistent hybrid between Fisherian and Neyman-Pearsonian methods (G Gigerenzer, 2004). A real-solution would advocate genuine statistical thinking and reasoning (G Gigerenzer, 1998) and would promote context-dependent analytical flexibility. It has been convincingly argued that Bayesian methods (particularly Bayesian parameter estimation) are a viable alternative (Kruschke & Liddell, 2015, 2017c).

validate our analytical results and to gain additional information that is not available in the frequentist framework. We performed a Bayes Factor analysis with appropriate "prior robustness checks". We also conducted a Bayesian bootstrap to compare results with the previous frequentist bootstrap analysis. Moreover, we utilised Bayesian parameter estimation via Markov chain Monte Carlo methods and tested our a prior hypotheses using a HDI (high density interval) and ROPE (region of practical equivalence) based decision algorithm. We were thus able to equate results from three different statistical/methodological perspectives (viz., analytic triangulation), thereby enabling convergent validation (Fielding, 2012).

2.2 A priori hypotheses

Our hypotheses were formulated *a priori* and they were derived from the pertinent quantum cognition literature (Atmanspacher, 2014a, 2016; Atmanspacher & Römer, 2012; Z. Wang et al., 2013). We specifically focused on sequential noncommutative effects in introspective visual judgments.

The directional (one-tailed) *a priori* hypotheses of primary interest were:

H_1: Measuring the luminance of high luminance stimuli first results in a decrease in the subsequent judgment for the low luminance stimuli as compared to the reverse order.

H_2: Measuring the luminance of low luminance stimuli first results in an increase in the subsequent judgment relative to reverse order.

In symbolic form expressed as follows:

H_A: $AB \neq BA$

where

A = high luminance visual stimuli

B = low luminance visual stimuli

Note that H_A can be expressed as a directional hypothesis (i.e., one-sided) by replacing "≠" with either "<" or ">".

2.3 Method

2.3.1 Participants and Design

The experiment was conducted in the psychology laboratory of the University of Plymouth (United Kingdom) and ethical approval was obtained from the universities human research ethics committee.

Eighty-two students from the University of Plymouth participated in this study (51 women and 31 men, ages ranging between 18 and 31 years, M_{age} = 21.73; SD_{age} = 4.17). Students were recruited via a cloud-based participant management software (Sona Experiment Management System®, Ltd., Tallinn, Estonia; http://www.sona-systems.com) which is hosted on the universities webserver. In addition, a custom-made website was designed in HTML, CSS, JavaScript, and "Adobe® Shockwave Flash - ActionScript 2.0" (Yam, 2006) to advertise the study in an attractive way to the student population (URL: http://irrational-decisions.com/sona/qp.html; see Appendix B2 for the source-code). Participants received either course credit or a payment of £8 for their participation.

2.3.2 Apparatus and materials

In order to support the open-source philosophy (Vainio & Vaden, 2012) and to facilitate replicability and the "openness of science" (Boulton et al., 2012) we used open-source software whenever this was feasible and uploaded all materials and the resulting dataset on our webserver at http://irrational-decisions.com/qp-exp1/.[92]

For the visual decision-making task, two singleton grey rectangles (dimensionality: 220 x 220px) with two different luminance levels were created using the open-source raster graphics editor GIMP (http://git.gnome.org/browse/gimp; see Peck, 2006). We utilised "Fechnerian scaling" (Dzhafarov, 2002; Dzhafarov & Colonius, 2001, 2005) for the design of the psychophysical stimuli, a psychophysical scaling technique which has also been implemented in the "`Fechner`" R package (Ünlü, Kiefer, & Dzhafarov, 2009). To systematically control stimulus luminance levels, we varied the V-parameter of the

[92] We are convinced that transparency should be one of the hallmarks of proper scientific research and nowadays there is no excuse why one should not make all material/data publicly available. Nowadays researchers can easily include a URL in all their publications or use the Open Science Framework (Foster, MSLS & Deardorff, MLIS, 2017), or similar repositories in order to foster "open knowledge" and "open data" (Boulton et al., 2012; Molloy, 2011). This would facilitate replication and, consequently, enhance the reliability of scientific findings. In addition it has been cogently argued that "open science is a research accelerator" (Woelfle, Olliaro, & Todd, 2011). The "replication crisis" is currently of great concern (Aarts et al., 2015; Baker, 2016; Munafò et al., 2017; Peng, 2015). A conscience discussion of this multifaceted "metascientific" topic is provided in a recent NATURE article (Schooler, 2014). Furthermore, this approach would enable other researchers to evaluate the validity of the reported findings by reanalysing the data (third party verification). Unbiased independent researchers who do not have any "unconscious" theory-driven vested interests (i.e., no confirmation bias) might discover patterns in the data which escaped the author's attention and they might be able to test novel hypotheses which were not part of the initial research agenda. Science should be a collective endeavour and ego-involvement should be minimized while knowledge accumulation should be the primary motif. Collectively, society would benefit from a more transparent approach towards science, especially in the long run. Moreover, openly publishing data could facilitate (possibly AI/machine learning driven) meta-analytic research (e.g., large-scale data mining). Such (semi-)automated procedures have the potential to significantly speed up general scientific progress. Furthermore, publishing negative results could potentially alleviate the long-standing and hitherto unresolved problem of α-error inflation (for more information on this crucial topic see http://irrational-decisions.com/?page_id=520)

HSV colour gamut (see Figure 14). The HSV colour model was created by Alvy Ray Smith in 1978 for computer graphics applications. HSV is an acronym for “hue, saturation, and value”, and is also often abbreviated with HSB (B for brightness). We chose the HSV model due to its geometric properties[93] and because previous experimental research showed that it displays reliable perceptual properties (Schwarz, et al., 1987). Furthermore, the HSV gamut allows for geometric (and symmetric/isomorphic) transformations which could be mapped onto projection vectors in the QP model in order to establish accompanying correlation coefficients. We created an interactive web-based example of the HSV model using “Adobe® Shockwave Flash - ActionScript 2.0” (Yam, 2006). The application can be accessed under the following URL:

http://irrational-decisions.com/?page_id=875

For the experimental stimuli, we applied the following parametrization to the V-value:

- High luminance stimuli: HSV: 0,0,60. (RGB: 153,153,153)
- Low luminance stimuli: HSV: 0,0,40. (RGB: 102,102,102)

The resulting visual stimuli can be downloaded from the following URLs as *.jpg files:

http://irrational-decisions.com/phd-thesis/visual-stimuli/low-luminance.jpg

http://irrational-decisions.com/phd-thesis/visual-stimuli/high-luminance.jpg

[93] The notion of subspaces of a Hilbert space is a geometrical one and quantum probability is oftentimes referred to as “projective probability” (Brody & Hughston, 2001; Busemeyer & Bruza, 2012; Z. Wang et al., 2013). Consequently, geometric colour spaces lend themselves as good candidates for exact quantitative modelling in future psychophysics experiments. Experimental results could then be correlated to the geometric quantum probability model by a talented mathematician/geometrician.

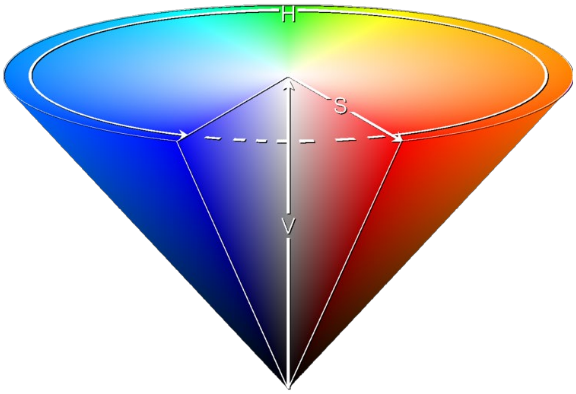

Figure 14. The HSV colour space lends itself to geometric modelling of perceptual probabilities in the QP framework.[94]

2.3.3 Experimental application in PsychoPy

The experiment was implemented in PsychoPy (J. W. Peirce, 2007, 2008) which is based on Python (Python Software Foundation, 2013). PsychoPy[95] is an open-source application for the design, programming, and presentation of experimental protocols with applicability to a broad array of neuroscience, psychology, and particularly psychophysics research. Although the stimuli timing functionality is a matter of ongoing debate, PsychoPy can achieve high levels of accuracy and precision with regards to the presentation of brief and quickly alternating visual stimuli (Garaizar & Vadillo, 2014). A detailed benchmark report can be found in Appendix B3. The

[94] It should be noted that the HSV model has several shortcomings. According to scientific nomenclature, lightness is defined as the perceived quantity of emitted light (and not emitted light itself as objectively measured). The HWB (Hue-Whiteness-Blackness) model has been suggested as an alternative based on a more intuitive mental model of colour space (Lou, Cui, & Li, 2006; A. R. Smith & Lyons, 1996). The conversion of HSV to HWB is as follows:
$H \rightarrow H$
$W \rightarrow (1 - S)\ V$
$B \rightarrow 1 - V$

[95] PsychoPy is a powerful viable alternative to proprietary software-packages like or E-Prime™ or Presentation™. Given that PsychoPy is entirely coded in Python (which can be utilised as a free alternative to Matlab™ (Blais, 2007; Jurica, 2009; Millman & Aivazis, 2011)), its capabilities can be extended with countless Python modules, packages, and libraries.

complete source code of the experiment (incl. visual stimuli) can be downloaded from the following URL as a compressed ZIP archive:

http://irrational-decisions.com/?page_id=618

2.3.4 Experimental Design

The basic structure of the experiment was a factorial repeated measures design in which the presentation order of two singleton visual stimuli with different luminance levels was randomly alternated in order to investigate noncommutative sequential effects in visual judgments (Bradley, 1958). We utilised a fully counterbalanced Latin-square design (Gaito, 1958; Grant, 1948). The experimental conditions were thus as follows:

V_{00} = low luminance → low luminance

V_{01} = low luminance → high luminance

V_{11} = high luminance → high luminance

V_{10} = high luminance → low luminance

The dependent variable was the condition dependent brightness rating which was recorded on a visual analogue scale as described in the ensuing subsection.

2.3.5 Procedure

Before the commencement of the study, participants were briefed (see Appendix B4) and accorded written informed consent (see Appendix B5). Subsequently, participants were seated in front of a personal computer (a detailed PC/graphic-card configuration report can be found in Appendix B3) and received further instructions.

2.3.6 Sequential visual perception paradigm

First, we collected general demographic information. Participants completed the form depicted in Figure 15.

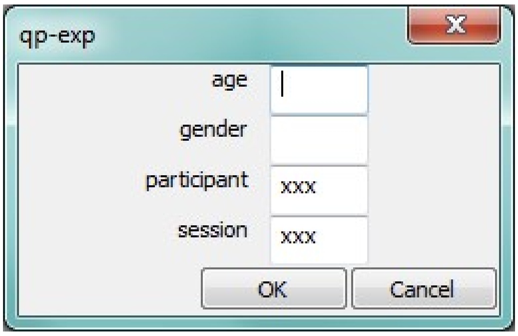

Figure 15. Demographic data collected at the beginning of the experiment.

After mouse clicking the “OK” button, the practice-phase of the visual perception paradigm was initiated. Participants were informed that they would perform a test of visual acuity which involved the perception of minute luminance differences. Participants were presented with a set of instructions (for verbatim transcript seeAppendix B6). Participants were required to judge the perceived brightness of a series of grey rectangles on a computerized visual analogue scale (Aitken, 1969), henceforth acronymized as VAS. The polar dimensionality of the VAS ranged from “not bright” to “very bright” (see Appendix B6 for screenshots). The respective VAS coordinates were automatically converted by PsychoPy into numerical values ranging from 1-10. We opted for a VAS because it allows for a more fine-grained continuous measure as compared to the widely employed discrete Likert scale (Likert, 1932); thereby increasing statistical sensitivity (i.e., discriminatory power) in the subsequent statistical analysis (for a direct comparison of both measurment apporaches see Van Laerhoven, Van Der Zaag-Loonen, & Derkx, 2004). An additional advantage of visual analogue scales over numerical rating scales is that the interval between values is not only interpretable as an ordinal measurement but also as an interval and ratio-type measurement (for an extended discussion see Price, Staud, & Robinson, 2012). It can thus be concluded that visual analogue scales have superior psychometric properties compared to their numerical counterparts. In PsychoPy, we fixed the precision parameter of the VAS to 100, i.e., each increment was subdivided into 1/100th of a tick-mark. This configuration enabled an extremely fine-grained measurement of responses. After each stimulus presentation, the VAS marker was by default automatically reset to the absolute midpoint of the scale. Before the commencement of the experimental trials, participants completed a practice block consisting of 4 trials. During the practice phase, participants were acquainted with the workings of the VAS and the general experimental procedure.

After that, the experimental block was automatically initiated. An experimental trial consisted of the presentation of a singleton grey rectangle which either displayed high luminance or low luminance. Stimulus presentation order was randomised within PsychoPy. In 50% of the trials participants had to judge the brightness of low luminance stimuli and in the remaining trials they were required to judge the brightness of high luminance stimuli. Stimuli were either preceded by stimuli of equivalent luminance (e.g., high luminance followed by high luminance) or by stimuli with different luminance levels (e.g., low luminance followed by high luminance). Each stimulus was presented for 60 frames (≈ 1000.2ms).[96] After a manual response was emitted (single left mouse click on the VAS), the next trial was automatically initiated (starting again with the visual fixation of the crosshair). In sum, the task of participants was to evaluate the visual stimuli which were presented in a randomly varying sequential order. In the PsychoPy backend, trials were programmatically organised in a loop. Randomization was archived by utilising the Python "`NumPy`" package (Van Der Walt, Colbert, &

[96] Vertical refresh rate of screen = 60Hz
1 frame = 1000ms/60 ≈ 16.67ms (frame to frame variability on average = 2.18ms)

Varoquaux, 2011). The exact temporal sequence of events within each trial is schematically visualised inFigure 16.

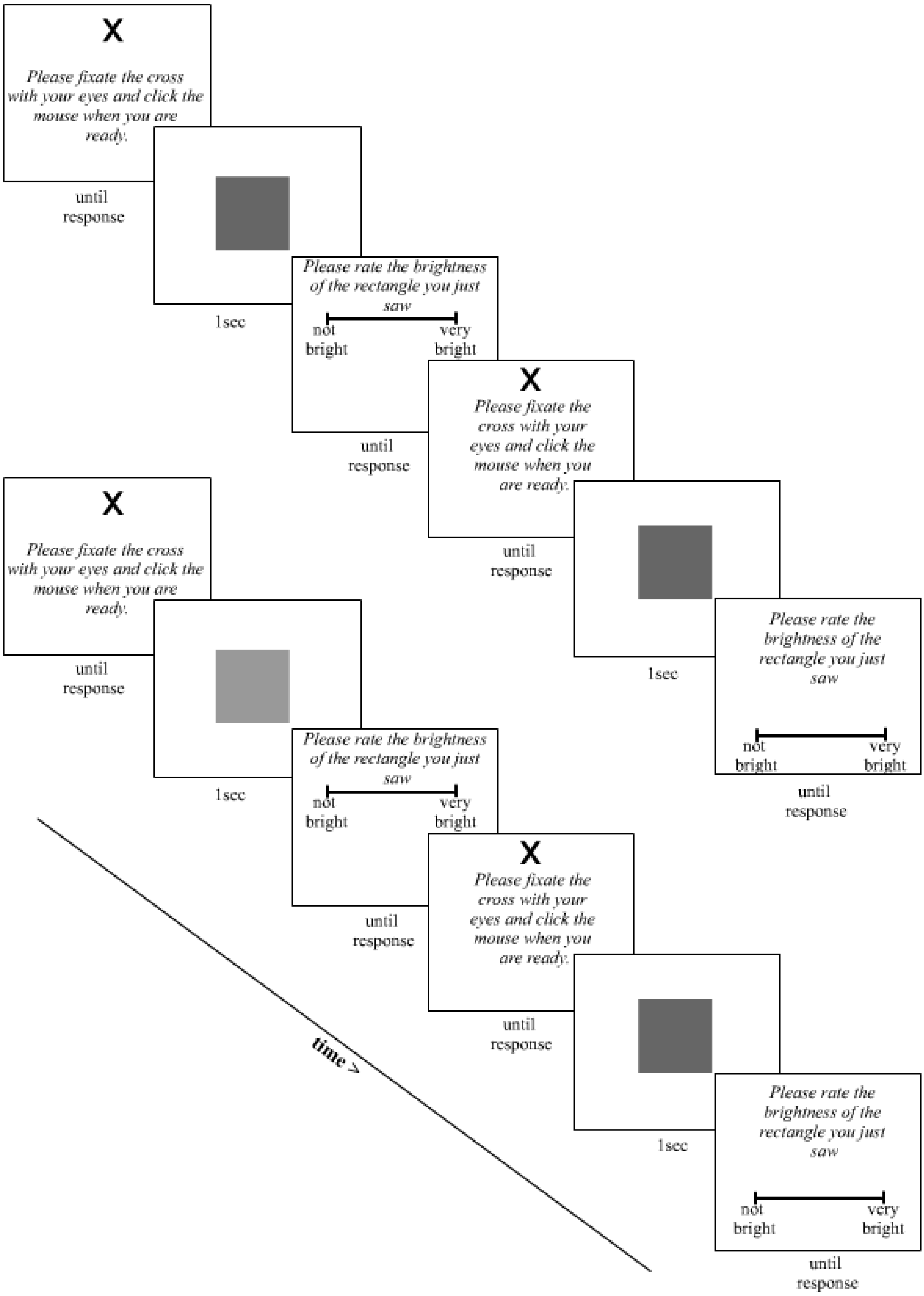

Figure 16. Diagrammatic representation of the experimental paradigm.

The within-trial sequence of events was as follows: Initially, a white fixation cross (crosshair) was displayed on a black background until a manual response (single left mouse-click) was emitted. The following instructions were presented to participants: "*Please fixate the cross with your eyes and click the mouse when you are ready*". Next, a rectangle of either high or low luminance appeared in the centre of the screen (screen size = 1920 x 1080, the application was executed in fullscreen mode) with a fixed duration of 60 frames. The rectangle was then replaced by a VAS rating request which was presented until a response was emitted. After that, the next rectangle appeared for the same temporal duration followed by the final rating request. In sum, each participant completed a total of 600 experimental trials. Upon completion of the experiment, participants were debriefed (see Appendix B7) and were given the possibility to ask questions concerning the purpose and theoretical background of the study. Finally, participants were thanked for their cognitive efforts and released.

2.3.7 Statistical Analysis

In order to test the formulated hypotheses, we utilised various parametric and non-parametric inferential statistical testing procedures. This was done in order to increase the robustness of our analyses and consequently the resulting logical inferences which are based on these calculations. Moreover, statistics is currently in a process of reformation (Cowles, 2014), especially in psychology and neuroscience. The "new statistics" are recommended by the APA and they are extending conventional Fisherian NHST with slightly more sophisticated inferential techniques (Cumming, 2012, 2013, 2014; Eich, 2014). Currently, classical NHST is unfortunately still the most dominant inferential approach in psychology and the bio-medial sciences (by a very large margin) and the APA recommendations do not really address the core of the issue which is the incompatible hybrid of Fishery and Neyman-Pearsonian methods. The vast majority of researchers exclusively utilise NHST in their analyses, despite the fact that NHST has been severely criticised on logical grounds (Cohen, 1995). The underlying syllogistic logic is widely misunderstood by the majority of professional researchers who are teaching their misinterpretations to students (Haller & Krauss, 2002), thereby perpetuating the delusional NHST meme. Consequently, logical conclusion based on NHST are frequently fallacious and invalid[97]. The consequences for the progress of science are obviously far reaching. We conducted a survey amongst researchers within the CogNovo programme and found that 17 out of 18 participants (professors, doctors and PhD students) were unable to interpret a simple independent samples *t*-test (see Appendix A8 for a synopsis of the survey). The results are representative of the larger population and have been replicated in various countries i.e., Germany, UK, USA (G Gigerenzer, 2004; Haller & Krauss, 2002). More than 80% of professional researchers who teach statistics at universities to students commit significant logical fallacies when asked to interpret a simple independent-samples t-test. The most common fallacy is the replication fallacy which fallaciously assumes that the p-value conveys information about the replicability of a given finding. Current statistical practices have been appropriately described as "mindless social rituals" by experts in the field of decision-making (G Gigerenzer, 1993, 2004; G Gigerenzer & Krauss, 2004). We are convinced that every scientist should ponder the logic of hypothesis testing because it lies at the very heart of the scientific endeavour. Critical thinking (instead of blind conformity to social norms) is of great importance for every serious researcher. It has been forcefully argued that "psychologists must change the way they analyse their data" in order to

[97] We discussed the "pitfalls of null hypothesis testing" extensively in a workshop and we also collected empirical data on the ubiquitous misinterpretation of *p*-values (see). The associated video is available under the following URL: http://www.cmharris.co.uk/?page_id=1444

improve the scientific discipline (Loftus, 1996; E. J. Wagenmakers, Wetzels, Borsboom, & Maas, 2011; E. J. Wagenmakers, Wetzels, Borsboom, & van der Maas, 2011) and we followed these sensible recommendations by utilising various nonconventional approaches.

In the subsequent analyses, we utilised the most promising "novel" statistical methodologies. We followed recent recommendation by the APA flagship journal "Psychological Science" which recently announced changes to its publication guidelines. We constructed confidence intervals and calculated effect-sizes for all parameters of interest. Moreover, we went one step further and constructed confidence interval for the effect sizes. We also went beyond the somewhat superficial recommendations and utilised the Vovk-Sellke maximum *p*-ratio (VS-MPR) to convert conventional *p*-values into a more readily interpretable format that is less prone to logical fallacies (Sellke et al., 2001; Vovk, 1993). Furthermore, we used bootstrapping techniques in order to check the robustness of our results and to maximise inferential power. We obtained bootstrapped confidence intervals for all parameters of interest. In addition to NHST, we conducted our analyses in different Bayesian frameworks in order to cross-validate our analytical results. We performed a Bayes Factor analysis with appropriate "prior robustness checks" and we computed a "Bayesian bootstrap" to compare results with the previous frequentist nonparametric bootstrap analysis. Moreover, we performed Bayesian parameter estimation using Markov chain Monte Carlo methods and tested our *a priori* hypotheses using a HDI (high density interval) and ROPE (region of practical equivalence) based decision-algorithm (Kruschke, 2014). We were thus able to equate results from various statistical paradigms (statistical triangulation), thereby increasing the verisimilitude of our inductive inferences (Festa, 1993).

2.3.8 Data treatment and statistical software

The PsychoPy-output was stored in comma-separated value files (*.csv files) which were merged into a single file. Each file included an anonymized participant ID, the date, and the starting time of the experiment, the demographic data, and the experimental data. Statistical analysis was primarily conducted by utilizing the open source software R v3.3.2 (R Core Team, 2013) and we extended its capabilities with the open-source RStudio IDE[98] v1.1.383 (RStudio Team, 2016). Moreover, we imported the "`ggplot`" library (Wickham, 2009, 2011) for plotting data. Furthermore, we utilised "`knitR`" v1.17 (Y. Xie, 2014, 2015) and "`Pandoc`" v2.0.0.1 (Krewinkel & Winkler, 2016; Krijnen, Swierstra, & Viera, 2014; Tenen & Wythoff, 2014) for automated dynamic document creation and conversion.

2.3.9 Frequentist NHST analysis

First, we computed various diagnostics (Table 1) and investigated the distributional characteristics of the data. In order to examine whether the data was normally distributed and to check for spurious outliers we utilised various visualisation techniques. We created Q-Q plots for all conditions (see Appendix B8) and median-based boxplots (Appendix B12). In addition, we visualised the data as using the "`beanplot`" package in R (Kampstra, 2008) (see Figure 17). Beanplots are a novel and creative way to visualise data (Juutilainen, Tamminen, & Röning, 2015). They provide much more detailed statistical/distributional information than conventional boxplots and line-graphs. Boxplots and related conventional visualisation techniques are regularly utilised to compare univariate data (Frigge, Hoaglin, & Iglewicz, 1989).

[98] IDE is an acronym for "Integrated Development Environment".

However, a significant disadvantage of classical boxplots is that they fail to display crucial distributional information. Moreover, they are not readily interpretable by non-mathematician (Kampstra, 2008). Beanplots are a viable alternative for visual comparison of univariate data between experimental conditions. Individual observations are displayed as small horizontal lines in a one-dimensional scatter plot. In addition, the estimated density of the distributions is displayed (we chose a Gaussian kernel) and the average is demarcated by a thick horizontal black line. Thusly, beanplots facilitate comparisons between experimental conditions and they enable the analyst to evaluate if the dataset contains sufficient observations to render the difference between experimental conditions meaningful from a statistical point of view. Furthermore, anomalies in the data (e.g., skewness, kurtosis, outliers, duplicate measurements, etc.) are readily identifiable in a beanplots (Kampstra, 2008). For purposes of direct between-group comparison, the associated R package provides the option to create a special asymmetric beanplot. We made use of this inherent function and created asymmetric beanplots which directly contrast the distributional characteristics of the pertinent experimental conditions (see Figure 18).

Table 1

Descriptive statistics for experimental conditions.

	N	**Mean**	**SD**	**SE**
v00	82	3.290	1.010	0.112
v10	82	3.710	0.930	0.103
v01	82	7.220	1.130	0.125
v11	82	6.690	1.070	0.118

2.3.10 Assumption Checks

Visual inspection of Q-Q plots (see Appendix B8) indicated that the Gaussianity assumption is satisfied, and that parametric hypothesis testing is appropriate for the data at hand (Wilk & Gnanadesikan, 1968). We utilised the R package "`moments`"[99] to evaluate skewness[100] and kurtosis[101] of the sample distributions. The indices of both distributional characteristics where within the ordinary range of ±2 and ±7, respectively (cf. Cain, Zhang, & Yuan, 2016; Groeneveld & Meeden, 1984), indicating that the data is neither saliently skewed nor overtly kurtic. We also performed formal *p*-value based significance tests of skewness and kurtosis, i.e., D'Agostino's K^2 skewness test (D'Agostino, 1970) and the Anscombe-Glynn kurtosis test (Anscombe & Glynn, 1983), both of which supported the stipulated Gaussianity assumption for all variables. Moreover, we computed the "Probability Plot Correlation Coefficient" (Filliben, 1975) for each experimental condition using the "`PPCC`"[102] package in R. The PPCC tests were performed with 10000 Monte Carlo simulations. The outcome of all four PPCC tests confirmed distributional Gaussianity (see Appendix B18). In addition, we tested for heteroscedasticity (i.e., $\sigma_1^2 \neq \sigma_2^2$) which is associated with the extensively studied Behrens-Fisher problem which may cause an inflated α-level (Sawilowsky, 2002).

[99] https://cran.r-project.org/web/packages/moments/moments.pdf

[100] The associated formula for the Fisher-Pearson coefficient of skewness is:
$\frac{\sum_{i=1}^{N} (Y_i - \bar{Y})^3 / N}{s^3}$, where $\bar{Y}$ signifies the mean, s the standard deviation, and N the number of data points.

[101] The definition of Pearson's measure of kurtosis is:
$\frac{\sum_{i=1}^{N} (Y_i - \bar{Y})^4 / N}{s^4}$, where $\bar{Y}$ signifies the mean, s the standard deviation, and N the number of data points.

[102] Available on CRAN: https://cran.r-project.org/web/packages/ppcc/ppcc.pdf

However, the ratio of variances confirmed homoscedasticity, i.e., the results of the *F*-test confirmed homogeneity of variances.[103]

[103] It is a common strategy to test for heteroscedasticity prior to a t-test. If the *F*-test on homogeneity of variances is statistically nonsignificant, the researcher continues with the parametric *t*-test. Otherwise alternative procedures (e.g., Welch-Aspin) which modify the degrees of freedom a required. However, this approach (i.e., making the *t*-test conditional on the *F*-test) can lead to an inflation of experiment-wise α-errors. That is, the sequential nature of protected testing automatically effects the nominal *α*-level. Moreover, it has been reported that a *F*-test protected *t*-test can lead to a significant loss in statistical power under Gaussianity (Sawilowsky, 2002). We will discuss issues associated with multiple hypotheses tests in more detail in the general discussion section in the context of α-inflation.

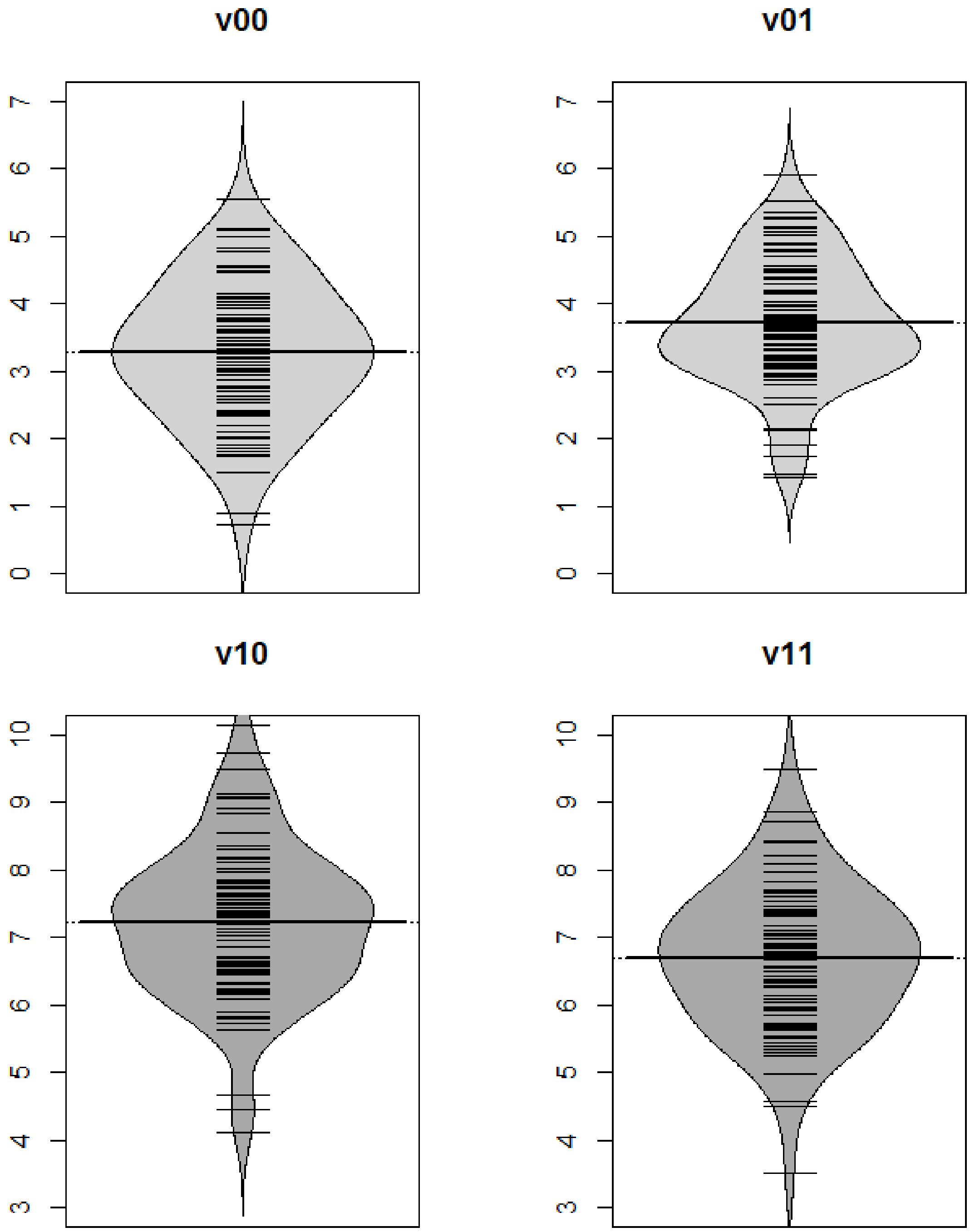

Figure 17. Beanplots visualising distributional characteristics of experimental conditions.

Note: *The thin horizontal black lines represent individual data points and the thick black line indicates the grand mean per condition. The shape of the bean visualises the density of the distributions (Gaussian kernel).*

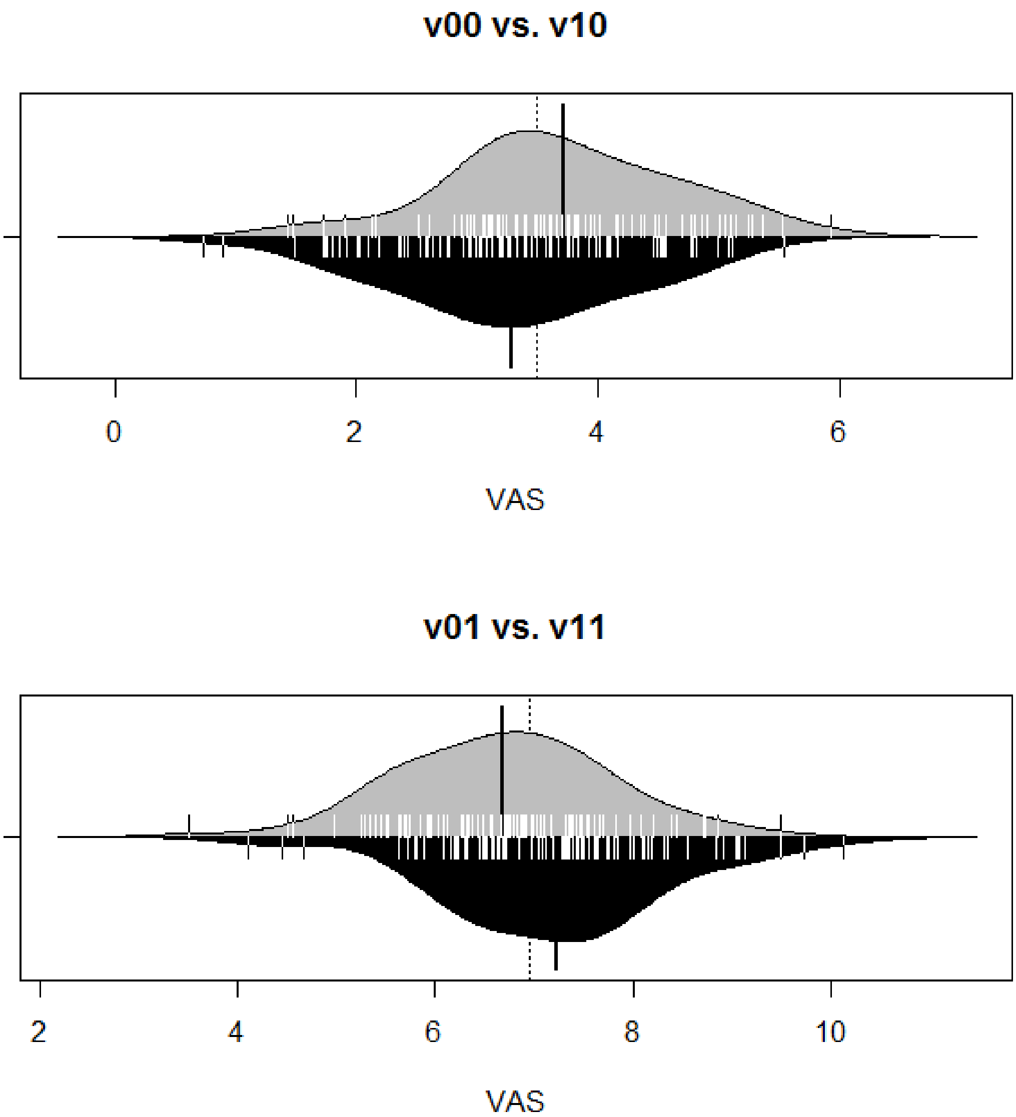

Figure 18. Asymmetric beanplots visualising pairwise contrasts and various distributional characteristics.[104]

[104] A high resolution (zoomable) vector graphic for closer inspection is available under the following URL: http://irrational-decisions.com/phd-thesis/beanplots-exp1.pdf
The associated R syntax can be found under the following URL: http://irrational-decisions.com/?page_id=2358

In order to investigate the distributional characteristics of the differences between means, we performed the Shapiro-Wilk's W test (S. S. Shapiro & Wilk, 1965). It has been demonstrated in large scale Monte Carlo simulation experiments (Razali & Wah, 2011) that the Shapiro-Wilk's W test[105] possess good characteristics (e.g., robustness, statistical power) in comparison to other popular tests of Gaussianity (e.g., Kolmogorov-Smirnov test, Lilliefors test, Anderson-Darling test, Cramér-von Mises test). The results reported in Table 2 suggest that Gaussianity can be assumed for the differences between means (the reported values refer to the mean brightness judgments to the second stimulus on each trial). Given that the normality assumption was satisfied we proceeded to test our hypotheses in a parametric inferential framework.[106]

Table 2

Shapiro-Wilk's W test of Gaussianity.

		W	**p**
v00	- v10	0.975	0.112
v01	- v11	0.986	0.533

Note. Significant results suggest a deviation from *Gaussianity*.

[105] The associated formula is $W = \frac{(\sum_{i=1}^{n} a_i x_{(i)})^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2}$.

[106] For the paired samples *t*-test, it is not important that the data is normally distributed per condition. The *t*-test merely assumes that the differences in means are normally distributed (this is evaluated by utilising *W*).

2.3.11 Parametric paired samples t-tests

In order to test our *a priori* formulated hypotheses[107] formally, we conducted two paired samples "Student" *t*-tests (Gosset, 1908). The results of both pairwise comparisons (two-tailed) were statistically significant at the conventional arbitrary α-level of 0.05 (R. Fisher, 1956). The first *t*-test indicated that low luminance stimuli were on average rated significantly lower in brightness when anteceded by equivalent stimuli (V_{00}; M=3.29, SD=0.93), as compared to low luminance stimuli anteceded by high luminance stimuli (V_{10}; M=3.71, SD=0.93), M_{Δ}=-0.42; $t(81)$=-3.07, p=0.003, 95%CI [-0.69, -0.15]; Cohen's d=-0.34,[108] 95%CI for d [-0.56, -0.12]. By contrast, the brightness of high luminance stimuli was on average rated significantly higher when the high luminance stimuli were anteceded by low luminance stimuli (V_{01}, M=7.22, SD=1.13), relative to high luminance stimuli anteceded by equivalent stimuli (V_{11}, M=6.69, SD=1.07), M_{Δ}=-0.53; $t(81)$=-3.43, p<0.001, 95%CI [0.22, 0.83]; Cohen's d=-0.38, 95%CI for d [-0.15, -0.60][109]. The effect was thus slightly more pronounced for the second orthogonal contrast. In sum , the analysis corroborated our *a priori* hypotheses and confirmed the predictions formulated by Atmanspacher & Römer (Atmanspacher & Römer, 2012). Given that multiple comparisons were conducted, it was necessary to apply a correction of α in order to prevent α-error inflation (i.e., the experimentwise error which has an identifiable maximum). We applied a classical single-step Bonferroni correction (O. J. Dunn, 1958, 1961) and adjusted the α-level accordingly.[110] Both comparisons remained

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[107] That is, the noncommutativity hypotheses AB ≠ BA described in section 2.2.

[108] Effect sizes were calculated based on the formula described by Moors (R. Fisher, 1956): $d = \frac{\bar{x}_1 - \bar{x}_2}{s}$ where the pooled standard deviation (s) is defined as $s = \sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}}$

[109] Given the widespread misinterpretation of conventional confidence intervals (Hoekstra et al., 2014) we provide additional tolerance intervals (Krishnamoorthy & Mathew, 2008) based on the Howe method (Howe, 1969) inAppendix B13.

[110] We utilised a classical single-step Bonferroni correction according to the following formula:

statistically significant at the conventional/normative level. However, given that we has directional a priori hypotheses and given that we only reported two-sided tests (in order to prevent controversies), it could be argued that the Bonferroni correction was unnecessary because the possible inflation of α was counterbalanced by the bidirectionality of the two hypotheses testing procedures, given that $p = 2 \cdot Pr(T > |t|)$, where T is the critical value of the Student distribution. However, the topic of α-inflation is of great importance for logically valid scientific inferences, but it is largely neglected by researchers[111]. We will discuss widespread issues associated with multiple comparison adjustments (i.e., experimentwise *and* familywise error rates) in greater detail in section 6.11.5.

In addition to the conventional parametric t-test, we computed the Wilcoxon signed-rank test (Wilcoxon, 1945) which provides a powerful nonparametric alternative to the t-test.[112] The Wilcoxon test computes the test statistic W and the corresponding p-value. It is a test of the null hypothesis (at the nominal α-level) that the distribution of the data is symmetric around a prespecified median value μ (i.e., μ = 0).[113] In the current analysis, W is utilised to test if the difference of the paired observations is centred symmetrically around μ = 0. For larger samples (>50) the test is based on a Gaussian

$p_i \leq \frac{\alpha}{m}$, where m signifies the total number of hypotheses tested.
Specifically, the Bonferroni procedure stipulates that H_1 should be rejected if $p_i \leq \frac{\alpha}{m}$ where p_i is the arbitrarily/idiosyncratically (Nuijten et al., 2016b) specified p-value for testing H_1.

[111] A meta-analysis of more than 30000 published articles indicated that less than 1% applied α-corrections for multiple comparisons even though the median number of hypothesis tests per article was 9 (Conover, 1973; Derrick & White, 2017; Pratt, 1959).

[112] Monte Carlo studies demonstrated that Wilcoxon test can be three to four times more powerful in detecting differences between means when the Gaussianity assumption is not met (R. C. Blair & Higgins, 1985; R. Clifford Blair & Higgins, 1980). Given that less than 5% of datasets in psychology are distributionally symmetric (Micceri, 1989), it has been argued that "the Wilcoxon procedure should be the test of choice" (Sawilowsky, 2002, p. 464). Moreover, Sawilowsky emphasizes the importance of habits which antagonise statistical innovation: "The t-test remains a popular test, however, most likely due to the inertia of many generations of classically parametrically trained researchers who continue its use for this situation" (Sawilowsky, 2002, p. 464).

[113] A limitation of the Wilcoxon test is that equivalent pairs are discarded from the analysis. If this is of particular concern, modified versions can be utilised (Charles, Jassi, Narayan, Sadat, & Fedorova, 2009).

approximation to calculate p. However, the Wilcoxon signed-rank test can also be used to compute exact statistics if the Boolean "`exact`" parameter is set to "`TRUE`" in R. In our analysis, this parametrisation did not make any meaningful difference. Hence, we only report the default test statistic. Moreover, the Hodges-Lehmann estimator (Lehmann, 1998; Oja, 2010) was employed to calculate confidence intervals for the nonparametric location parameter and the matched rank biserial correlation (Cureton, 1956; Woolson, 2008) was utilised to calculate nonparametric effect sizes[114] (with associated 95% confidence intervals).

In résumé, the results of the Wilcoxon tests were in line with the conclusions derived from the *t*-tests (even though the exact numerical values diverged). Both methods (parametric vs. nonparametric) indicated statistically significant differences between experimental conditions and confirmed our *a priori* predictions concerning noncommutativity in visual perceptual judgments. The statistical results of both analyses are summarised in Table 3 and a visual synopsis is provided in

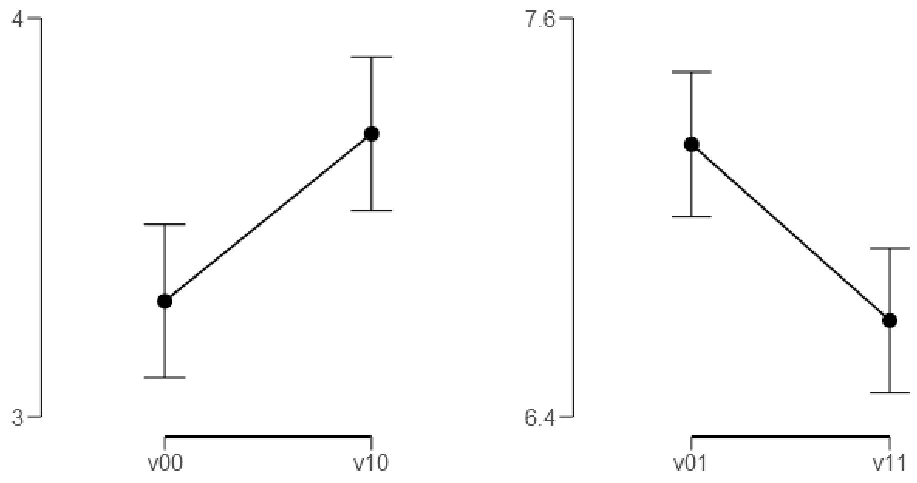

Figure 19. "Connected boxplots" are available under the following URLs:

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[114] If exact p-values are available, an exact confidence interval is obtained by the algorithm described in Bauer (1972).

- http://irrational-decisions.com/phd-thesis/connected-boxplots-exp1-v00-v10.pdf
- http://irrational-decisions.com/phd-thesis/connected-boxplots-exp1-v01-v11.pdf

In addition, the complete results are summarised under the following URL:

http://irrational-decisions.com/phd-thesis/results-exp1.html

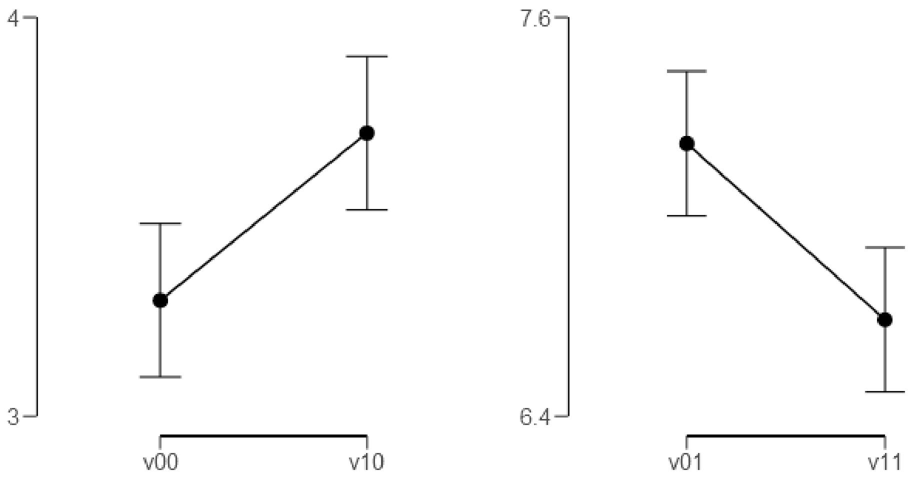

Figure 19. Statistically significant differences between grand means of experimental conditions and their associated 95% confidence intervals.

Table 3

Paired samples t-tests and nonparametric Wilcoxon signed-rank tests

								95% CI for Location Parameter			95% CI for Effect Size	
	Test	**Statistic**	**df**	**p**	**VS-MPR***	**Location Parameter**	**SE Difference**	**Lower**	**Upper**	**Effect Size**	**Lower**	**Upper**
v00 - v10	Student	-3.071	81	0.003	21.69	-0.420	0.137	-0.692	-0.148	-0.339	-0.561	-0.116
	Wilcoxon	1089.000		0.005	14.69	-0.471		-0.714	-0.160	-0.360	-0.555	-0.127
v01 - v11	Student	3.427	81	< .001	55.04	0.530	0.155	0.222	0.838	0.378	0.153	0.601
	Wilcoxon	2442.000		< .001	79.89	0.544		0.239	0.838	0.435	0.214	0.614

* Vovk-Sellke Maximum p -Ratio: Based on the p -value, the maximum possible odds in favor of H_1 over H_0 equals $1/(-e\, p \log(p))$ for $p \leq .37$ (Sellke, Bayarri, & Berger, 2001).

Note. For the Student t-test, location parameter is given by mean difference d ; for the Wilcoxon test, effect size is given by the Hodges-Lehmann estimate.

Note. For the Student t-test, effect size is given by Cohen's d ; for the Wilcoxon test, effect size is given by the matched rank biserial correlation.

2.3.12 Bayes Factor analysis

In this section, we report a Bayes Factor analysis with robustness checks for various priors and a sequential analysis for the evolution of the Bayes Factor as a function f of the number of participants (i.e., a time series of evidential flow). We conducted the Bayes Factor analyses using the "`BayesFactor`" package (Richard D. Morey, Rouder, & Jamil, 2014) in R. In addition, we utilised the open-source software JASP[115] which is based on the same R package. The dataset, the results, and the corresponding JASP analysis script can be downloaded from the following URL to facilitate "analytical reviews" as recommended by Sakaluk, Williams, & Biernat (2014): http://irrational-decisions.com/phd-thesis/exp1.jasp.[116] At the conceptual meta level, the primary difference between the frequentists and the Bayesian account is that the former treats data as random and parameters as fixed and the latter regards data as fixed and unknown parameters as random. Given the "cognitive context" (pertinent background knowledge is lacking), and in order to keep the analysis as objective as possible (objective Bayes[117]), we avoided opinionated priors and applied a noncommittal

[115] JASP is currently dependent on more than 100 R packages. An up-to-date list of the included R packages can be found under the following URL: https://jasp-stats.org/r-package-list/

[116] This allows the interested reader to replicate the analysis with various idiosyncratic parametrisations, e.g., in a "subjective Bayes" framework (Berger, 2006).

[117] For more information on "objective Bayesianism" we refer the interested reader to a pertinent publication by Berger (1977).

(diffuse) Cauchy prior[118] as advocated by Sir Harold Jeffreys (Jeffreys, 1939, 1946, 1952)[119].

"*The prior distribution is a key part of Bayesian inference and represents the information about an uncertain parameter that is combined with the probability distribution of new data to yield the posterior distribution, which in turn is used for future inferences and decisions.*" (Gelman, 2006, p. 1634)

Instead of using the standard Cauchy distribution that was Jeffreys' default choice (r = 1), we set the scale parameter of the Cauchy distribution to $1/\sqrt{2} \approx 0.707$, the present *de facto* standard in the field of psychology (Gronau, Ly, & Wagenmakers, 2017). We fixed the location parameter for the effect size of the prior distribution under H_1 to $\delta = 0$. It has been pointed out that Bayes factors with the Cauchy prior are slightly biased towards H_0 (Rouder, Speckman, Sun, Morey, & Iverson, 2009), i.e., the Cauchy prior is slightly conservative towards H_1. The noninformative (noncommittal) parametrisation of the Bayesian model we applied is as follows ("objective Bayes" (Berger, 2006)):

H_1: $\delta \sim \text{Cauchy}(0,r)$

A Bayes Factor can range from 0 to ∞ and a value of 1 denotes equivalent support for both competing hypotheses. Moreover, LogBF_{10} can be expressed as a logarithm

---

[118] In a seminal paper entitled "Inference, method, and decision: towards a Bayesian philosophy of science" Rosenkrantz (Rosenkrantz, 1980, p. 485) discusses the Popperian concept of verisimilitude (truthlikeness) w.r.t. Bayesian decision making and develops a persuasive cogent argument in favour of diffuse priors (i.e., C-systems with a low λ). In a related publication he states: "If your prior is heavily concentrated about the true value (which amounts to a 'lucky guess' in the absence of pertinent data), you stand to be *slightly* closer to the truth after sampling than someone who adopts a diffuse prior, your advantage dissipating rapidly with sample size. If, however, your initial estimate is in error, you will be farther from the truth after sampling, and if the error is substantial, you will be much farther from the truth. I can express this by saying that a diffuse prior is a better choice at 'almost all' values of [q1] or, better, that it semi~dominates any highly peaked (or 'opinionated') prior. In practice, a diffuse prior never does much worse than a peaked one and 'generally' does much better…" (1946)

[119]Mathematically, Jeffreys' prior is defined as follows: $p(\vec{\theta}) \propto \sqrt{det\mathcal{I}(\vec{\theta})}$. It has the advantage that it is scale invariant under various reparameterizations, for details see Jeffreys (e.g., G Gigerenzer & Hoffrage, 1995).

ranging from -∞ to ∞. A BF of 0 denotes equal support for H_0 and H_1. Appendix B20 contains additional information on the Bayes Factor, the choice of priors, and various advantages of Bayes Factor analysis over NHST.

For the first pairwise comparison we computed (experimental condition V_{00} vs. V_{10}), we obtain a Bayes Factor of $BF_{10} \approx 9.12$ indicating that the data are about 9 times more likely under H_1 than under H_0, i.e., $P(D \mid H_1) \approx 9.12$. The probability of the data given H_0 can be found by taking its reciprocal which results in $BF_{01} \approx 0.11$, viz., $P(D \mid H_0) \approx 0.11$. The second comparison (V_{01} vs. V_{11}) produced a Bayes Factor of $BF_{10} \approx 24.82$, i.e., $P(D \mid H_1) \approx 24.82$; $P(D \mid H_0) \approx 0.04$. The associated errors were extremely small for both contrasts as can be seen in

Table 4. According to Jeffreys' interpretational schema, the first Bayes Factor (condition V_{00} vs. V_{10}) provides "moderate evidence for H_1" and the second Bayes Factor (V_{01} vs. V_{11}) provides "strong evidence for H_1" (see Table 5). Descriptive statistics and the associated 95% Bayesian credible intervals are given in Table 6. In addition, the results are visualised in Figure 20 and Figure 21, respectively.

Table 4

Bayes Factors for the orthogonal contrasts

			BF_{10}	error %
v00	-	v10	9.199	1.129e -7
v01	-	v11	24.818	7.631e -8

Table 5

Qualitative heuristic interpretation schema for various Bayes Factor quantities (adapted from Jeffreys, 1961).

Bayes Factor	**Evidentiary value**
> 100	Extreme evidence for H_1
30 - 100	Very strong evidence for H_1
10 -30	Strong evidence for H_1
3 - 10	Moderate evidence for H_1
1 - 3	Anecdotal evidence for H_1
1	No evidence
1/3 - 1	Anecdotal evidence for H_0
1/10 - 1/3	Moderate evidence for H_0
1/30 - 1/10	Strong evidence for H_0
1/100 - 1/30	Very strong evidence for H_0
< 1/100	Extreme evidence for H_0

Table 6

Descriptive statistics and associated Bayesian credible intervals.

					95% Credible Interval	
	N	**Mean**	**SD**	**SE**	**Lower**	**Upper**
v00	82	3.290	1.010	0.112	3.068	3.512
v10	82	3.710	0.930	0.103	3.506	3.914
v01	82	7.220	1.130	0.125	6.972	7.468
v11	82	6.690	1.070	0.118	6.455	6.925

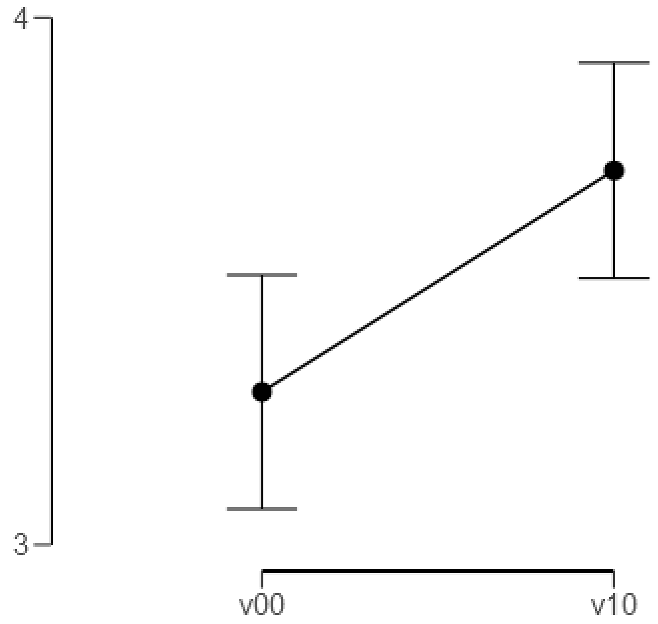

Figure 20. Comparison of V_{00} vs. V_{10} (means per condition with associated 95% Bayesian credible intervals).

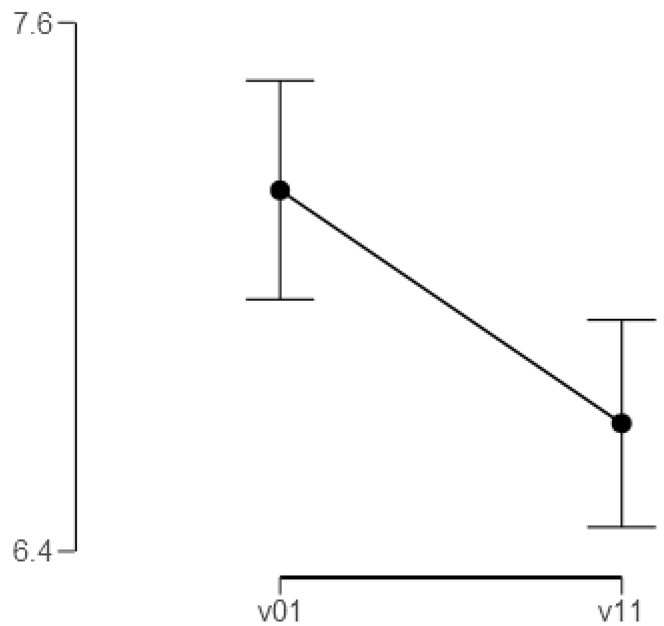

Figure 21. Comparison of condition V_{01} vs. V_{11} (means per condition with associated 95% Bayesian credible intervals).

Figure 23 provide a visual synopsis of the most essential results of the Bayesian analysis in a concise format: 1) a visualisation of the prior distribution of the effect sizes, 2) the associated posterior distributions, 3) the associated 95% Bayesian credible intervals, 4) the posterior medians, 5) the Bayes Factors, 6) the associated Savage–Dickey density ratios[120] (E. J. Wagenmakers, Lodewyckx, Kuriyal, & Grasman, 2010), 7) proportion wheels[121] of the Bayes Factor in favour of H_1.

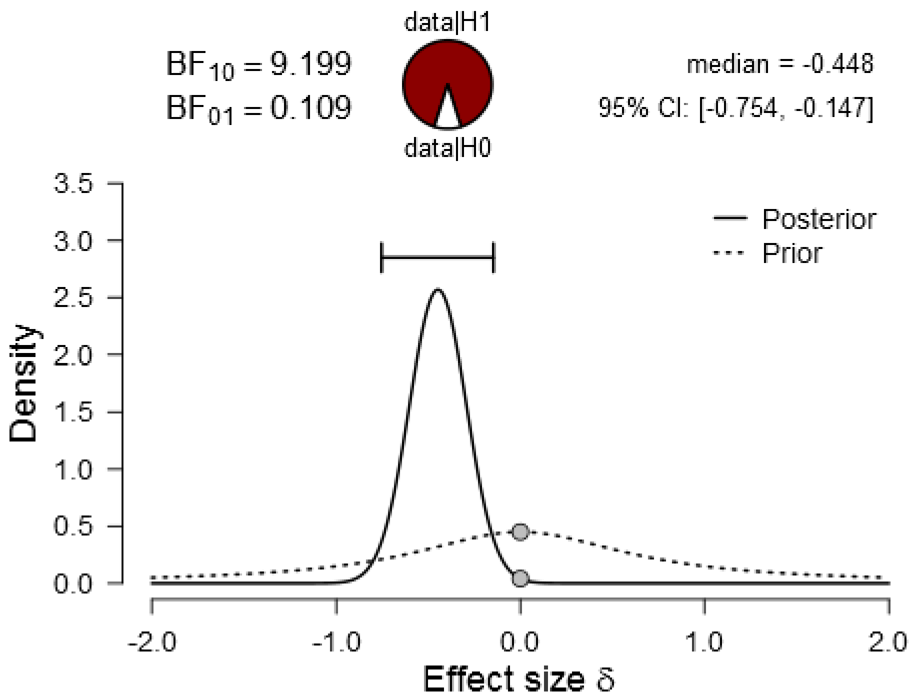

Figure 22. Prior and posterior plot for the difference between V_{00} vs. V_{10}.

[120] For an interactive visualisation see http://irrational-decisions.com/?page_id=2328

[121] The proportion wheels provided an intuitive representation of the strength of evidence associated with the Bayes factor. The odds are transformed to a magnitude between 0 and 1 and visualised as the corresponding proportion of the circle. The following analogy has been articulated to facilitate an intuitive understanding of the "proportion wheel" concept (it has been convincingly argued that analogy is the core of cognition (Hofstadter, 1982, 1995)): "*Imagine the wheel is a dartboard; you put on a blindfold, the wheel is attached to the wall in random orientation, and you throw darts until you hit the board. You then remove the blindfold and find that the dart has hit the smaller area. How surprised are you? The level of imagined surprise provides an intuition for the strength of a Bayes factor.*" (E.-J. Wagenmakers et al., 2017, p. 6)

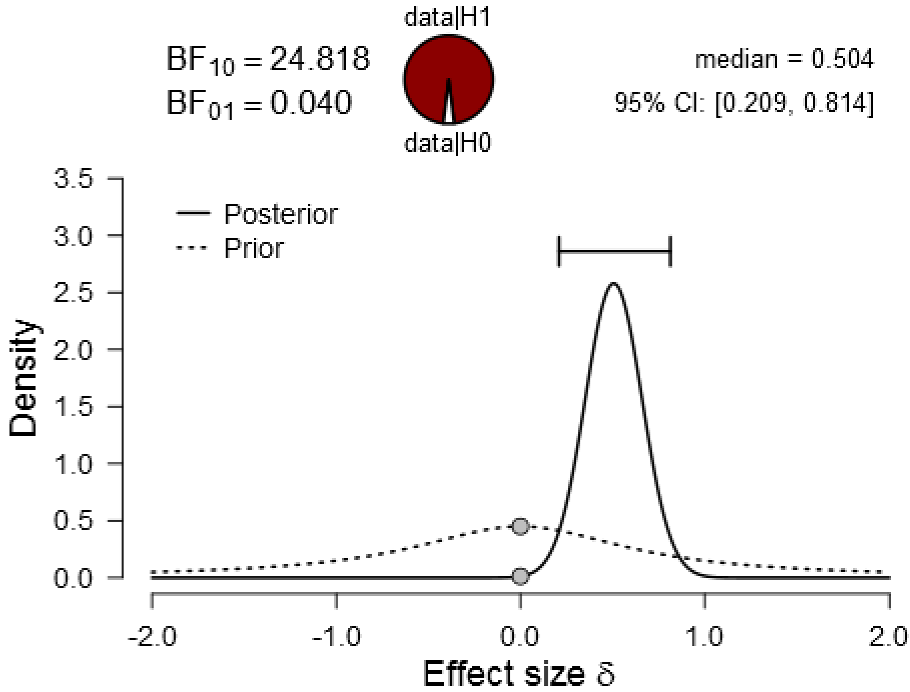

Figure 23. Prior and posterior plot for the difference between V_{01} vs. V_{11}.

In addition, we conducted a Bayes Factor robustness for various Cauchy priors per pairwise comparison, respectively. Specifically, we contrasted Cauchy priors ranging from [0, 1.5]. The results are visually summarised in

Figure 24 and

Figure 25, respectively. For the first comparison (V_{00} vs. V_{10}) the maximum Bayes Factor was obtained at $r \approx 0.28$ (max $BF_{10} \approx 12.56$). For the second comparison (V_{01} vs. V_{11}) the maximum evidence in favour of H_1 was associated with $r \approx 0.32$ (max $BF_{10} \approx 31.31$). Based on this analysis, it can be concluded that the Bayes Factor is robust under various reparameterizations of *r*.

Bayes Factor Robustness Check

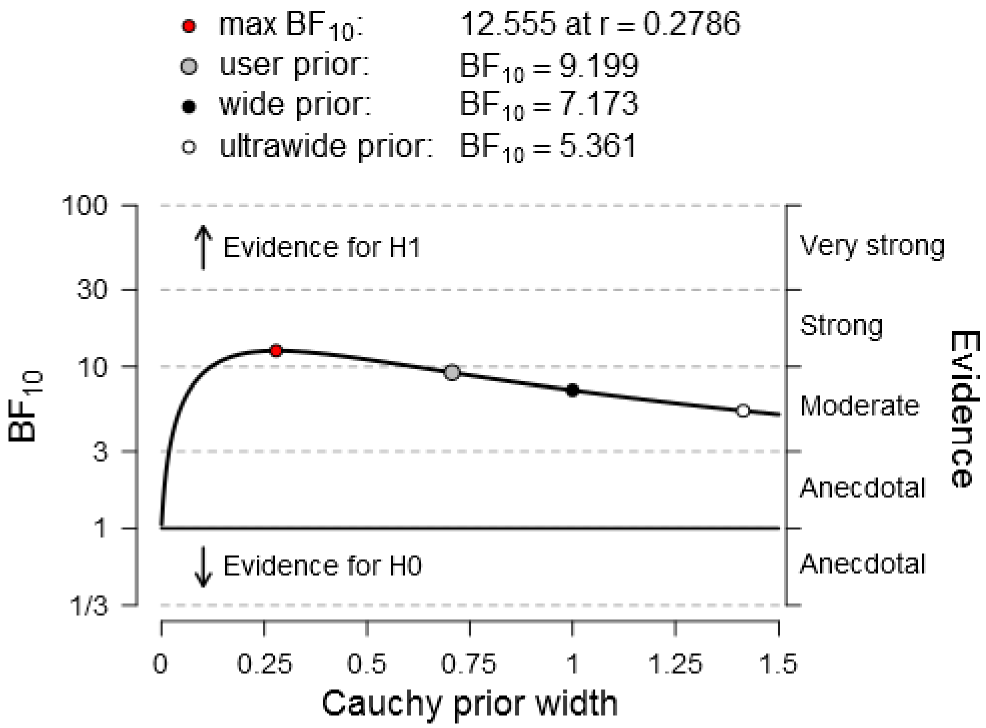

Figure 24. Visual summary of the Bayes Factor robustness check for condition V_{00} vs. V_{10} using various Cauchy priors.

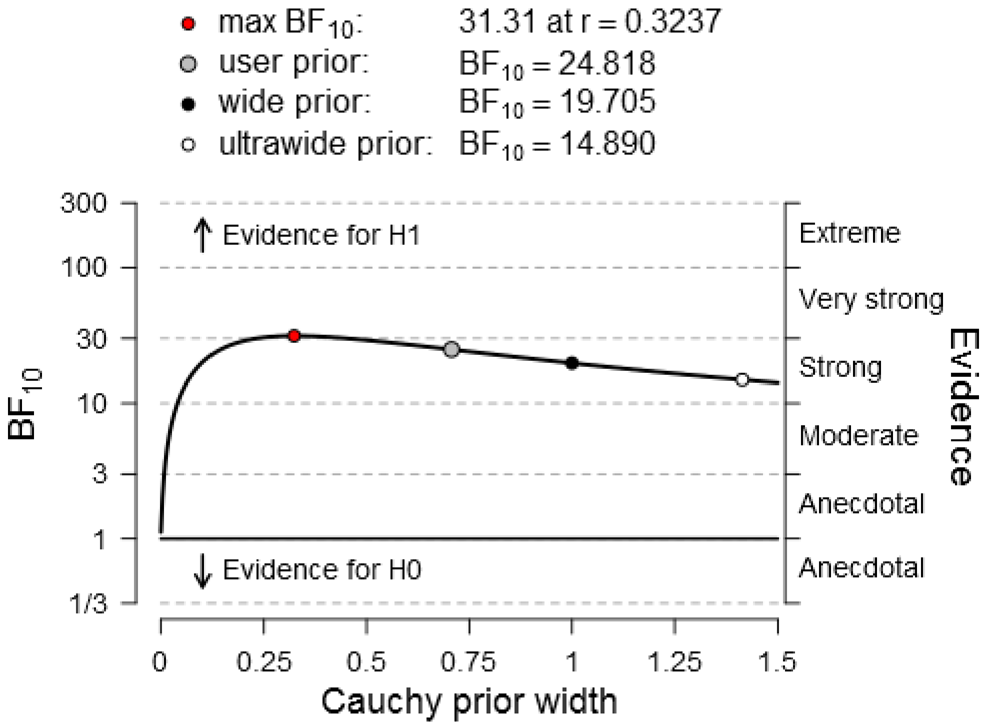

Figure 25. Visual summary of the Bayes Factor robustness check for condition V_{01} vs. V_{11} using various Cauchy priors.

Furthermore, we carried out a sequential Bayes Factor analysis. This allowed us to inspect the accumulation of evidence in favour of H_1 as a function of the number of data points/participants. *Prima vista*, it can be seen that the evidence in favour of H_1 increases as *n* accumulates. The results per experimental condition are visualised in Figure 26 and Figure 27, respectively.

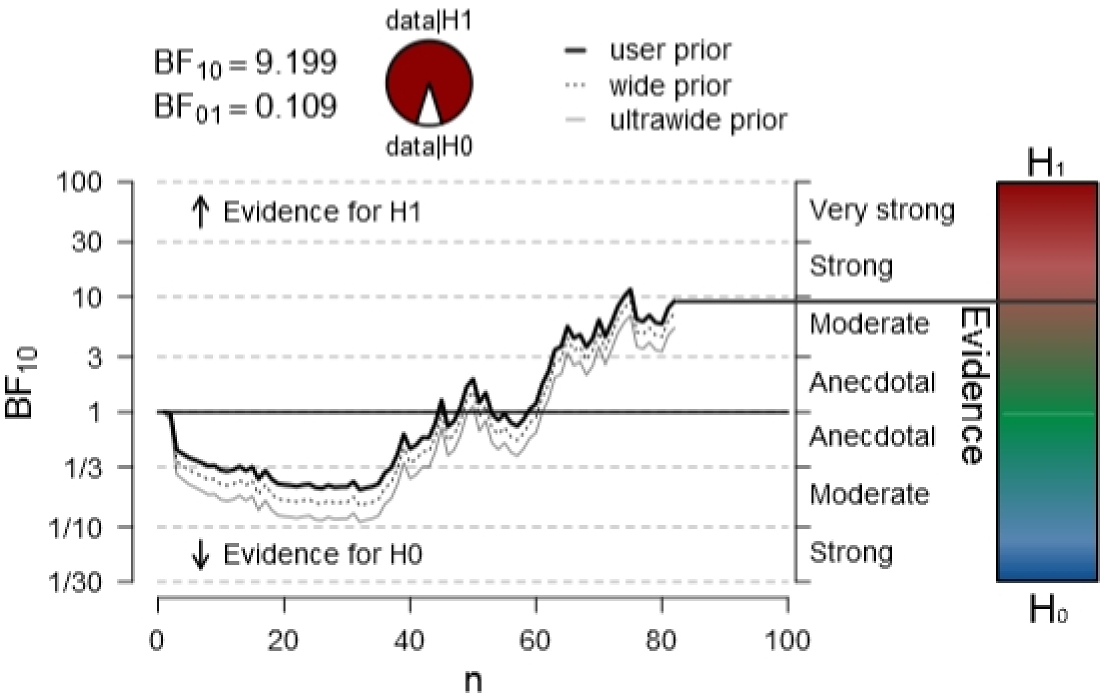

Figure 26. Sequential analysis depicting the flow of evidence *as n* accumulates over time (experimental condition V_{00} vs. V_{10}).

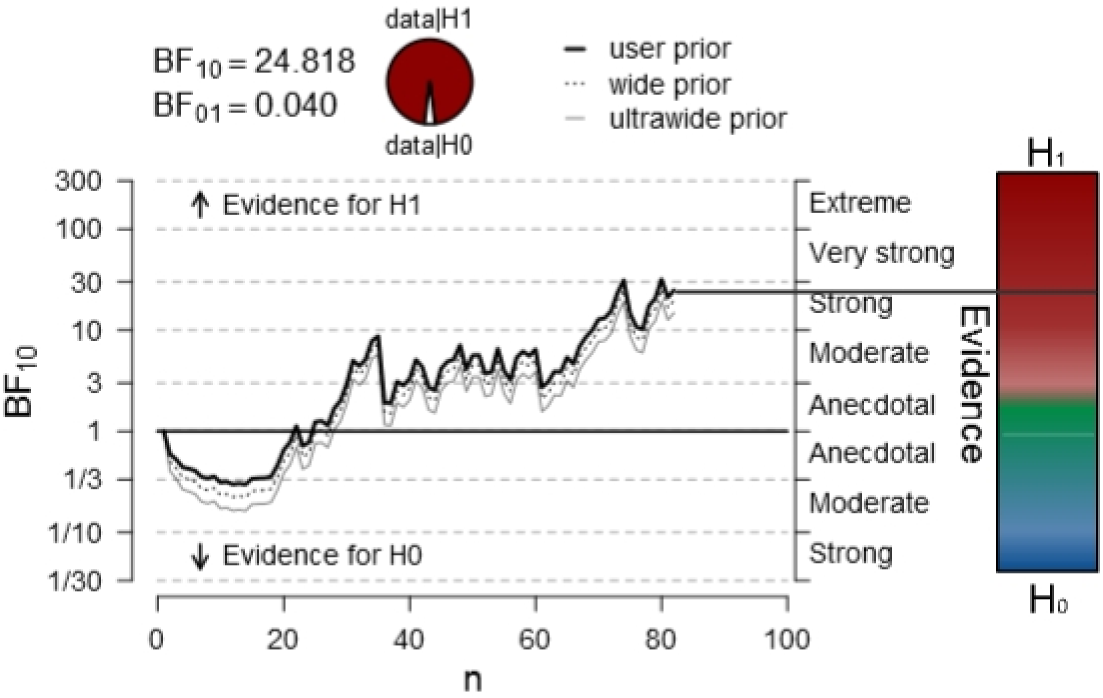

Figure 27. The visualisations thus show the evolution of the Bayes Factor (y-axis) as a function of *n* (x-axis). In addition, the graphic depicts the accrual of evidence for various Cauchy priors (experimental condition V_{01} vs. V_{11}).

A crucial advantage of Bayes Factor analysis over frequentists hypothesis testing is that in contrast to frequentist NHST (which can only reject H_0), Bayes Factor analysis allows to quantify evidence in favour of H_0 (thereby circumventing the inferential asymmetry associated with NHST). In addition to the graphical and numerical representation of the evolution of the Bayes Factor (evidential flow) for various prior choices, we colour-coded[122] the graded BF_{10} in favour of H_1 vs. H_0.

[122] The color-coding of the Bayes Factor was accomplished by creating a vector graphic with a gradient based on a complementary colour triplet (hexadecimal colours: #8B0000, #008B46, #00468B). This visual representation provides an intuitive "feeling" for the strength of evidence in favour of H_1 and reduces the demand for abstract though associated with numerical statistical inferences as it maps numerical values on an intuitively interpretable colour gradient. It has been shown in various contexts that the format in which statistical information is presented influences subsequent inferential conclusions (Tooby & Cosmides, 2005; Wason, 1968). From an evolutionary psychology point of view, it has been argued that logically sound scientific reasoning can be facilitated when information is presented in non-abstract terms (Baumeister et al., 1998). Statistical inference involves decision-making. Repeated

Next, we performed a Bayesian parameter estimation analysis using MCMC methods in order to obtain precise posterior intervals for all parameters of interest. It should be noted that the results of both Bayesian approaches do not necessarily converge, that is, they can lead to diverging inferential conclusions. For instance, when the posterior high density interval does not include zero the Bayes Factor can contrariwise indicate that H_1 should not be preferred over H_0. This seemingly paradoxical situation can lead to confusions and it should be emphasised that Bayesian analysts do not necessarily agree on which approach to take. While some advocate Bayes Factor analysis, other advocate the Bayesian parameter estimation approach.

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decision-making depletes executive functions (Hagger et al., 2010), that is, the higher-order cognitive processes which underpin logical thinking are a limited resource (Bechara, Tranel, & Damasio, 2000; Gailliot, 2008) which can be easily depleted, presumably due to reduction of prefrontal glycogen storage (de Neys et al., 2013; Kahneman, 2003) – an argument which makes sense in an evolutionary perspective, i.e., for our ancestors glucose was a limited nutritional resource and we still run this outdated program – hence we crave it, store it (e.g., obesity), and conserve it whenever possible. In the context of cognitive depletion and decision-making, it has been empirically demonstrated that the quality of juridical decision-making is subject to ego-depletion (Danziger, Levav, & Avnaim-Pesso, 2011). Given that hypothesis testing is in many ways analogous to juridical decision-making, this empirical finding may be transferable to inferential statistical decision-making. It has been shown in various domains of thinking and reasoning that humans are “cognitive misers” (Kahneman & Tversky, 1974) and that the quality of decisions is compromised if this limited (System 2) capacity is overworked (de Neys et al., 2013). Abstract numerical statistical reasoning is particularly demanding on prefrontal executive functions. Therefore, statistical information should be presented in an intuitively/heuristically interpretable format whenever this is possible in order to improve the quality of inferential reasoning. Graphical representation like color-coded evidence are an effective way to achieve this desideratum. Insights from cognitive linguistics, e.g., conceptual metaphor theory (Lakoff, 1993; Lakoff & Johnson, 1980; Lakoff & Nuñez, 2000) can be successfully utilised to present statistical information in a more intuitive and less error-prone format.

2.3.13 Bayesian a posteriori parameter estimation via Markov Chain Monte Carlo simulations

This section reports the application of Bayesian *a posteriori* parameter estimation via Markov Chain Monte Carlo (MCMC) simulations. It has been demonstrated that this method is a very powerful approach to statistical analysis and inference (Gelman, Carlin, Stern, & Rubin, 2004). The Bayesian parameter estimation approach can be regarded as a superior mathematical alternative to conventional NHST *t*-tests (and related frequentist methods, e.g., ANOVA). It produces posterior estimates for means, standard deviations (and their differences) and effect sizes (Kruschke, 2013). In contrast to the dichotomous decisions which are inferred from conventional *t*-tests, the Bayesian parameter estimation approach provides probability distributions of the parameter values of interest. Furthermore, the Bayesian approach does not rely on the distributional assumptions which are stipulated by parametric *t*-tests and it is relatively insensitive to outliers. In addition, the procedure can be used to calculate credible intervals around point estimates. For these reasons, it is clearly superior to conventional NHST (Kruschke, 2013; Kruschke & Liddell, 2015, 2017a; Kruschke & Vanpaemel, 2015).

Specifically, we conducted Bayesian analyses with computations performed by the Gibbs-sampler JAGS (Plummer, 2005). JAGS is a "flexible software for MCMC implementation" (Depaoli, Clifton, & Cobb, 2016). We were particularly interested in measures of central tendency derived from the posterior distribution in order to evaluate differences between experimental conditions. In addition, we also estimated additional metrics (e.g., quantiles) of the posterior to gain a more complete picture.

Relatively recent advances in technology make these computationally demanding methods feasible. The combination of powerful microprocessor and sophisticated computational algorithms allows researchers to perform extremely powerful Bayesian statistical analyses that would have been very expensive only 15 years ago and virtually impossible circa 25 years ago. The statistical "Bayesian revolution" is relevant for many scientific disciplines (Beaumont & Rannala, 2004; S. P. Brooks, 2003; Gregory, 2001; Shultz, 2007) and the scientific method in general. This Kuhnian-paradigm shift (T. Kuhn, 1970) goes hand in hand with Moore's law (G. E. Moore, 1965) and the exponential progress of information technologies (Kurzweil, 2005) (cf. Goertzel, 2007) and the associated ephemeralization[123] (Heylighen, 2008).

Model comparison via Bayes Factor (Bayesian confirmation theory) as described in the antecedent section is thus not the only viable Bayesian alternative to classical frequentist NHST. Bayesian parameter estimation and Bayes Factor analysis differ in significant ways: Compared to Bayes Factor analysis, the Bayesian parameter estimation approach provides much richer information because it results in a posterior probability distribution on all parameters (Bayes Factor analysis does not). Model comparison and Bayesian parameter estimation are both committed to Bayes' theorem as the axiomatic foundation for probabilistic inductive inferences. However, the questions they address are fundamentally different (Steel, 2007). Whereas model comparison is concerned with the evaluation (i.e., confirmation/rejection) of hypotheses, Bayesian parameter estimation is primarily concerned with the computation of posterior probability distributions for the parameters of interest. However, the Bayesian parameter estimation approach can also be utilised to test specific research hypotheses. In the model comparison approach, the decision (accept vs. reject) is based on a predefined arbitrary threshold (i.e., the strength of the Bayes Factor). In the

[123] A concept popularised by Buckminster Fuller which is frequently cited as an argument against Malthusianism.

parameter estimation approach, on the other hand, the inferential decision is based on the specification of a threshold for the parameter under investigation (viz. a "posterior high density interval" in combination with a "region of practical equivalence"). The parameter estimation approach and its associated methods for hypothesis testing will be described in more detail in the following subsections.

In sum, both Bayesian methods base their decision rules on the posterior distribution. However, given that they focus on different facets of the posterior distribution the resulting logical inferences do not necessarily have to coincide (Kruschke, 2014). Furthermore, both inferential approaches are based on the notion of credence (a subjective "Bayesian" probability describing the level of confidence or belief). Given that subjectivity involves the epistemological idiosyncrasies and propensities of a human cogniser, credence must be regarded as a psychological property.

While hypothesis testing plays a pivotal role in psychology and the biomedical sciences, it is ancillary in many other scientific disciplines (e.g., physics). Many disciplines that do not primarily rely on hypothesis testing focus on estimation and modelling. A common problem in statistical modelling is to estimate the values of parameter of a given probability distribution. Bayesian Parameter Estimation (BPE) methods provide a set of powerful and robust statistical tools to obtain these values. In other words, BPE can produce accurate approximations to the Bayesian posterior distributions of various parameters (θ, i.e., theta) of interest. That is, parameters are modelled as probability distributions. BPE utilises computationally expensive Markov chain Monte Carlo (MCMC) algorithms to achieve this goal. In contrast to NHST, BPE fixes the empirical data and instead assumes a range of credible values for θ. Moreover, BPE allows probabilities to represent credibility (i.e., subjective certainty/belief). Hence, a semantically more appropriate alternative nomenclature for BPE (and all other Bayesian methods) would be "statistical uncertainty modelling".

In the experimental context at hand, we applied Bayesian parameter estimation methods to our empirical data in order to obtain accurate estimates of the parameter values of interest. Based on the *a priori* defined hypotheses, we were particularly interested in the posterior distribution of the means per condition, their standard deviations, and the difference between means. BPE provides informative posterior probability distributions for all parameters of interest.

In the subsequent subsection we will provide a brief introduction to Bayesian parameter estimation via Markov chain Monte Carlo methods. After that, we will describe the actual Bayesian analysis and the results. The section is subdivided as follows (according to the sequential steps of the analysis):

1. Overview of the utilised software
2. Definition of the descriptive model and specification of priors
3. MCMC computations of the posterior distributions
4. Diagnostics/assessment of MCMC convergence
5. Summary and interpretation of the resulting posterior distributions within the pertinent theoretical framework

The Bayesian inferential approach we employed provides rich information about the estimated distribution of several parameters of interest, i.e., it provides the distribution of the estimates of μ and σ of both experimental conditions and the associated effect sizes. Specifically, the method provides the "relative credibility" of all possible differences between means, standard deviations (Kruschke, 2013). Inferential conclusions about null hypotheses can be drawn based on these credibility values. In contrast to conventional NHST, uninformative (and frequently misleading[124]) *p* values are redundant in the Bayesian framework. Moreover, the Bayesian parameter estimation approach enables the researcher to accept null hypotheses. NHST, on the other, only allows the researcher to reject such null hypotheses.

The critical reader might object why one would use complex Bayesian computations for the relatively simple within-group design at hand. One might argue that a more parsimonious analytic approach is preferable. Exactly this question has been articulated before in a paper entitled "Bayesian computation: a statistical revolution" which was published in the Philosophical Transactions of the Royal Society: "*Thus, if your primary question of interest can be simply expressed in a form amenable to a t test, say, there really is no need to try and apply the full Bayesian machinery to so simple a problem*" (S. P. Brooks, 2003, p. 2694).

The answer is straightforward: "*Decisions based on Bayesian parameter estimation are better founded than those based on NHST, whether the decisions derived by the two methods agree or not. The conclusion is bold but simple: Bayesian parameter estimation supersedes the NHST t test*" (Kruschke, 2013, p. 573).

Bayesian parameter estimation is more informative than NHST[125] (independent of the complexity of the research question under investigation). Moreover, the conclusions drawn from Bayesian parameter estimates do not necessarily converge with those based on NHST. This has been empirically demonstrated beyond doubt by several independent researchers (Kruschke, 2013; Rouder et al., 2009).

[124] For more detailed information on the frequent logically fallacious misinterpretations of *p*-values and related frequentist statistics see chapter xxx.
[125] It is also more informative than Bayes factor analysis.

2.3.13.1 Software for Bayesian parameter estimation via MCMC methods

In order to conduct the Bayesian parameter estimation, we utilised several open-source software packages (all are all freely available on the internet). We created a website were the associated URLs are compiled: http://irrational-decisions.com/?page_id=1993

Analyses were entirely conducted in R using the "BEST" package (Kruschke, 2014). Best is an acronym for "Bayesian Estimation Supersedes the *t*-Test". Moreover, we installed JAGS "Just Another Gibbs Sampler" (Plummer, 2003, 2005) and RStudio (RStudio Team, 2016). BEST has numerous (recursive) reverse dependencies and reverse import dependencies which can be found with the R code provided in Appendix E6. The utilised programs have been described in great detail two recent textbooks on Bayesian analysis (Kruschke, 2010a, 2014).

2.3.13.2 Mathematical foundations of Bayesian inference

Bayesian inference allocates credibility (i.e., belief) across the parameter space Θ[126] of the model (conditional on the *a priori* obtained empirical data). The mathematical axiomatic basis is provided by Bayes' theorem. Bayes' theorem derives the probability of θ given the empirical data in terms of its inverse probability (i.e., the probability of the data given θ and the prior probabilities of θ). In other word "Bayesian data analysis involves describing data by meaningful mathematical models, and allocating credibility to parameter values that are consistent with the data and with prior knowledge" (Kruschke & Vanpaemel, 2015, p. 279)

[126]Uppercase Theta (Θ) denotes the set of all possible combinations of parameter values in a specific mathematical model (the joint parameter space). Lowercase theta (θ) on the other hand, denotes a single k-dimensional parameter vector.

The mathematical formula for the allocation of credibility across parameters is axiomatized in Bayes' theorem (Bayes & Price, 1763), i.e., Bayes' theorem mathematically defines the posterior distribution on the parameter values in a formal manner.

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)}$$

Where:

- $P(A)$ signifies the prior (the preliminary belief about A)
- $P(B)$ signifies the evidence
- $P(A|B)$ signifies the posterior probability (the belief about of A given B)
- $P(B|A)$ signifies the likelihood.

Applied to the current analysis Bayes' theorem takes the following form:

$$\underbrace{p(\mu_1, \sigma_1, \mu_1, \sigma_1, \nu\ |D)}_{posterior} = \underbrace{p(D \mid \mu_1, \sigma_1, \mu_1, \sigma_1, \nu)}_{likelihood} \text{ x } \underbrace{p(\ \mu_1, \sigma_1, \mu_1, \sigma_1, \nu)}_{prior}\ /\ \underbrace{p(D)}_{evidence}$$

Equation 8. Bayes' theorem (Bayes & Price, 1763) as specified for the hierarchical descriptive model utilised to estimate θ.

let D be the empirical data, μ_1 and μ_2 the means per experimental condition (e.g., condition V_{00} and V_{10}), σ_1 and σ_2 the associated standard deviations, and ν the normality parameter.

Bayes' theorem emphasises the posterior (conditional) distribution of parameter values (the Latin terminus *"a posteriori"* signifies empirical knowledge which proceeds from experiences/observations). The factors of Bayes' theorem have specific meaning assigned to them: The “evidence” for the specified model, *p(D)*, equals the total probability of the data under the model which can be computed by averaging over the parameter space Θ (Kruschke, 2015). Each parameter value is weighted by the “strength of belief” in the respective values of θ. For the current model, Bayes’ theorem can be semantically summarised as follows: It signifies that the posterior probability of the combination of parameter values (i.e., $< \mu_1, \mu_2, \sigma_1, \sigma_2, \nu >$) is equal to the likelihood of that parameter value combination multiplied by the prior probability of that parameter combination, divided by the constant $p(D)$. This constant is often referred to as the “*evidence”* for the model and is also called the “*marginal likelihood function”* (Kruschke, 2013). Its numerical value is calculated by taking the average of the likelihood, $p(D|\theta)$, across all values of θ (i.e., over the entire parameter space Θ), weighted by the prior probability of θ (Kruschke, 2014). The posterior distribution is thus always a compromise between the prior believability of the parameter values and the likelihood of the parameter values, given data. (Kruschke, 2010b). Our experimental data was measured on a visual analogue scale (VAS) ranging across a continuum of values. Given the extremely fine-grained nature of our measurements the resulting numerical values are “quasi-continuous”. Therefore, all parameters are regarded as continuous variables for all practical purposes. It thus follows that the posterior distribution is continuously distributed across the joint parameter space Θ (Kruschke et al., 2017).

Given that Bayesian parameter estimation (BPE) is currently no methodological standard in psychology we will provide some terminological clarifications of the underlying Bayesian nomenclature. The credibility of the parameter values after the empirical observation is termed the “posterior distribution”, and the believability of the parameter values before the empirical observation is termed the “prior distribution”. The probability of the observation for a particular parameter value combination, is called the "marginal likelihood function". It indicates the degree to which the observed outcome is anticipated, when averaged across all possible values of the weights, scaled proportionally to their respective believability (Kruschke, 2008). The denominator labelled as "evidence", *p(D),* is the marginal likelihood also referred to as "model evidence". In BPE, Bayes' theorem is used to make inferences about distribution parameters, i.e., the conditional distribution of θ is calculated given the observed data. The question is: What is the probability of θ conditional on the observed data? The prior is an unconditional distribution associated with θ. In contrast to NHST, θ is not assumed to be random, we are merely nescient[127] of its value. In other words, probability is conceptualised as a state of subjective belief or state of knowledge (as opposed to objective "pure" probability as an intrinsic property of θ).

The posterior distribution is approximated by a powerful class of algorithms known as *Markov chain Monte Carlo* (MCMC) methods (named in analogy to the randomness of events observed at games in casinos). MCMC generates a large representative sample from the data which, in principle, allows to approximate the posterior distribution to an arbitrarily high degree of accuracy (as $t \to \infty$). The MCMC sample (or chain) contains a large number (i.e., > 1000) of combinations of the parameter values of interest. Our model of perceptual judgments contains the following parameters: $< \mu_1, \mu_2, \sigma_1, \sigma_2, \nu >$ (in all reported experiments). In other words, the MCMC algorithm randomly samples a very large n of combinations of θ from the posterior distribution. This representative sample of θ values is subsequently utilised in order to estimate various characteristics of the posterior (Gustafsson, Montelius, Starck, & Ljungberg, 2017), e.g., its mean, mode,

[127] The term "nescienct" is a composite lexeme composed of the Latin prefix from *ne* "not" + *scire* "to know" (cf. "science"). It is not synonymous with ignorant because ignorance has a different semantic meaning ("to ignore" is very different from "not knowing").

median/medoid, standard deviation, etc. The thus obtained sample of parameter values can then be plotted in the form of a histogram in order to visualise the distributional properties and a prespecified high density interval (i.e., 95%) is then superimposed on the histogram in order to visualise the range of credible values for the parameter under investigation.

For the current Bayesian analysis, the parameter space Θ is a five-dimensional space that embeds the joint distribution of all possible combinations of parameter values (Kruschke, 2014). Hence exact parameter values can be approximated by sampling large numbers of values from the posterior distribution. The larger the number of random samples the more accurate the estimate. A longer MCMC chain (a larger sample) provides a more accurate representation (i.e., better estimate or higher resolution) of the posterior distribution of the parameter values (given the empirical data). For instance, if the number of MCMC samples is relatively small and the analysis would be repeated the values would be significantly different and, on visual inspection, the associated histogram would appear "edgy". With larger MCMC samples, the estimated values (on average) approximate the true values of the posterior distribution of the parameter values and the associated histogram becomes smoother (Kruschke, 2014). The larger the MCMC sample size the higher the accuracy because the sample size n is proportional to the "Monte Carlo Error" (MCE; i.e., accuracy is a function of MCMC sample size). To sum up, the MCMC approach clearly yields approximate parameter values and its accuracy depends on the number of values n that are used to calculate the average. Quantitative methods have been developed to measure the Monte Carlo Error "objectively" (Elizabeth Koehler, Elizabeth Brown, 2009), however, this intricate topic goes beyond the scope of this chapter. Of great relevance for our purpose is the fact that this analytic approach also allows to compute the credible difference of means between experimental conditions by computing $\mu_1 - \mu_2$ for every combination of sampled values. Moreover, BPE provides a distribution of credible effect sizes. The same distributional information can be obtained for the differences between σ_1 and σ_2 (and the associated distributional range of credible effect sizes). To sum up, BPE is currently one of the most effective statistical approaches to obtain detailed information about the various parameters of interest.

2.3.13.3 Model specifications – A hierarchical Bayesian descriptive model

In order to carry out the Bayesian parameter estimation procedure, we first defined the prior distribution. The to be estimated parameters relevant for the hypotheses at hand were: the means μ_1 and μ_2; the standard deviation σ_1 and σ_2 and the normality parameter ν. We were particularly interested in the a priori predicted difference between experimental conditions, i.e., $\mu_1 - \mu_2$. The main purpose of the Bayesian parameter estimation was thus to estimate these parameters and to quantify the associated uncertainty (i.e., credibility) of these approximations[128]. We defined a descriptive model for the Bayesian parameter estimation which is outlined in the following subsection. We ascribed an appropriate prior distribution to all five parameters (see Figure 28) according to the specification described in Kruschke (2013, 2015; Kruschke &

[128] In this situation, Stein's paradox (2012) is applicable, given that more than three parameters are estimated simultaneously (i.e., the dimensionality of the multivariate Gaussian distribution Θ is ≥ 3). The mathematical paradox is well-known in decision theory and estimation theory and it points out the inadmissibility of the he ordinary decision rule for estimating the mean when multiple m-variate Gaussian random vectors are involved

(i.e., if $m \geq 3$). Ergo, in the estimation scenario at hand, the ordinary estimator $\hat{\theta}$ is a suboptimal approximation of θ. A compact mathematical proof (based on partial integration) of this counterintuitive phenomenon has recently been formulised by Samworth (1987; 1981). However, from a pragmatic point of view, it is still very reasonable to use the empirical data as an estimate of the parameters of interest, viz., to use $\hat{\theta}$ as an estimate of θ, since empirical measurements are distorted by independent Gaussian noise with $\mu = 0$.

Meredith, 2012). The prior distribution specified for each parameter is as follows: The empirical data (x) is described by a *t*-distribution (the wider tails make the t-distribution more robust compared to the Gaussian distribution, i.e., it is less sensitive to outliers). The *t*-distribution has three parameters: the mean (μ), the scale parameter (σ), and the degrees of freedom (v). Low values of v are associated with wider tails (v can be regarded as a "shape parameter"). As v get larger the t-distribution converges to a Gaussian (see Appendix B21 for a visualisation of various v parametrisations).

In order to make the prior distribution tolerable for a sceptical audience we chose noncommittal (diffuse) priors which signify a lack of prior knowledge about the conceivable values of the parameters of interest. Defining the prior distribution in such vague (noncommittal) terms indicates that it has a negligible impact on the estimation of the posterior distribution. In other words, by choosing noninformative priors we ensured that the data governs the inference. All priors were specified according to the model detailed in Kruschke (2013). For precise mathematical derivations see Kruschke (2014).

2.3.13.4 Definition of the descriptive model and specification of priors

The parameters μ1 and μ2 are modelled by a normal distribution. In concordance with Kruscke (2013) the standard deviation of μ was expressed in very broad terms (SDpooled x 1000). The mean M of the prior distribution of μ was defined a M_{pooled} (the pooled mean of the empirical data). The prior distribution for σ_1 and σ_2 was also noninformative, i.e., a wide uniform distribution with hyperparameters ranging from L=SDpooled /1000 to H 1000xSD_{pooled}. In practical terms, the resulting priors are extremely wide and approximate a uniform distribution raging from -∞ to ∞. Lastly, the prior distribution for a shifted exponential (λ=29, shifted+1) was defined for the normality index ν (for mathematical details see Kruschke, 2013, Appendix A). As a simplifying assumption, it is postulated that the degree of normality ν is equivalent for both experimental conditions. The probabilistic model is visualised in Figure 28.

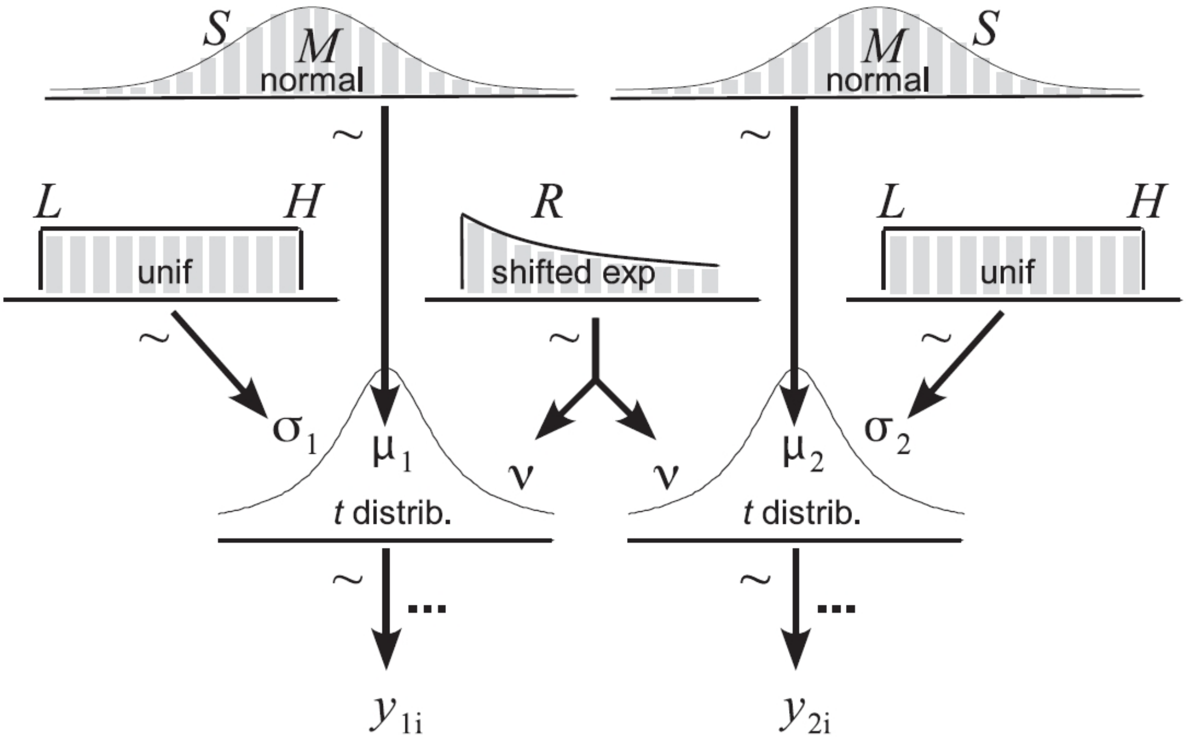


Figure 28. Hierarchically organised pictogram of the descriptive model for the Bayesian parameter estimation (adaptd from Kruschke, 2013, p. 575)[129].

Legend:

- S = standard deviation;
- M = mean;
- L =low value;

[129] R code for generating pictograms of hierarchical Bayesian models is available on GitHub under the following URL: https://github.com/rasmusab/distribution_diagrams

- H = high value;
- R = rate;
- unif = uniform;
- Shifted exp = shifted exponential;
- distrib. = distribution

The experimental data from condition V_{00} (y_{1i}) and V_{10} (y_{2i}) are located at the bottom of the pictogram. These data are described by heavy tailed and broad (noncommittal) *t*-distributions[130]. The data are randomly distributed (~) and the conditions have unique parameters for the respective means and standard deviations, i.e., μ_1, μ_2, and σ_1, σ_2, correspondingly. The parameter for the normality index ν is equivalent and thus shared between conditions. Summa summarum, we defined four unique types of distributions for the five-dimensional parameter space Θ. The respective distributions were parametrised in such a way that prior commitment has a minimal impact on the posterior (i.e., we adopted a non-informative "objective" Bayesian approach).

As can be seen in Figure 29 and Figure 30 the Student *t*-distribution (invented by Gosset, 1908; a.k.a. Student)[131] is more centred around 0. In comparison to the Gaussian distribution, the *t*-distribution has heavy tails. The height of the tails is denoted by the Greek letter ν (nu). A heavy-tailed distribution has a large ν (e.g., a value of 90). A small ν on the other hand, signifies an approximation of the Gaussian distribution. Hence, ν can be regarded as a quantitative tail-index of a given probability density function. If ν has a small parameter, the distribution can represent data with outliers very well. In the subsequent analysis, data from each experimental condition will be described with a *t* distribution. Each condition has its individual mean and standard

[130] Note that the t-distribution is stipulated as the distribution for the data. By contrast, the NHST t-test utilises the t-distribution as a distribution of the sample mean divided by the sample standard deviation.
[131] For a historical discussion see Fisher-Box (1938) and Neyman (Meyn & Tweedie, 1993).

deviation. Because we did not observe many extreme values (i.e., spurious outliers) we will use an identical tail-index ν for both conditions (Kruschke, 2013). In sum, we will utilise Bayesian estimation for the following five parameters: μ_1, μ_2, σ_1, σ_2, and ν.

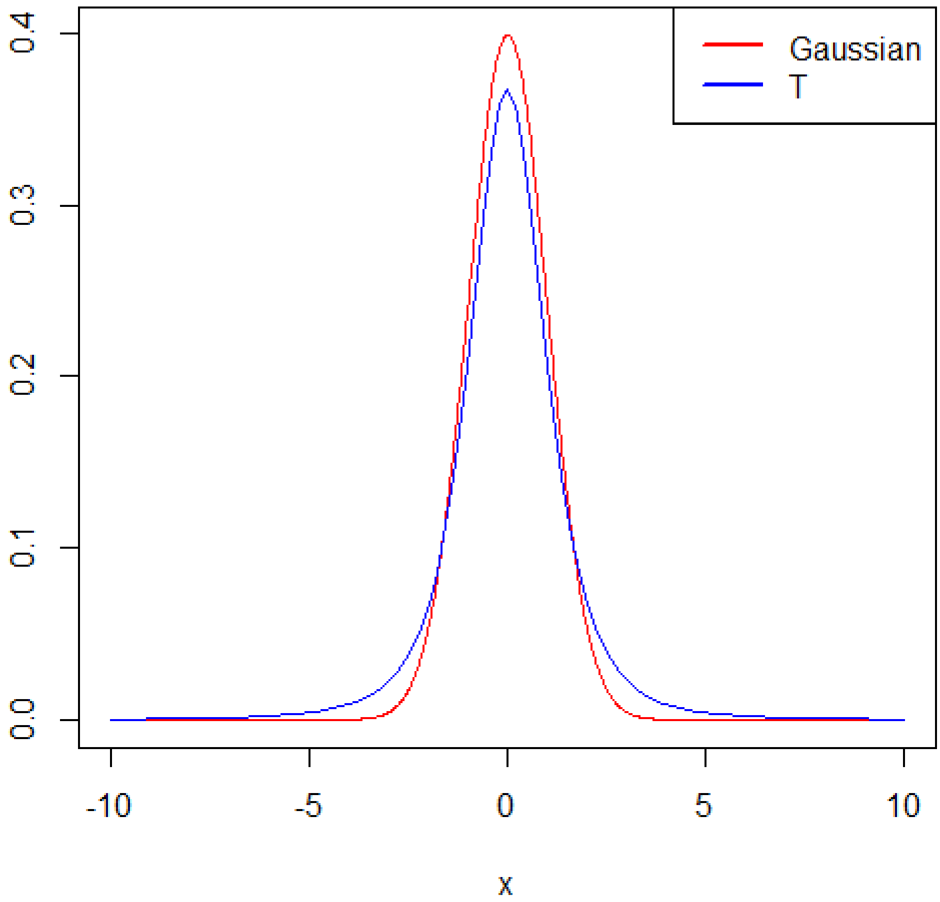


Figure 29. Visual comparison of the Gaussian versus Student distribution.

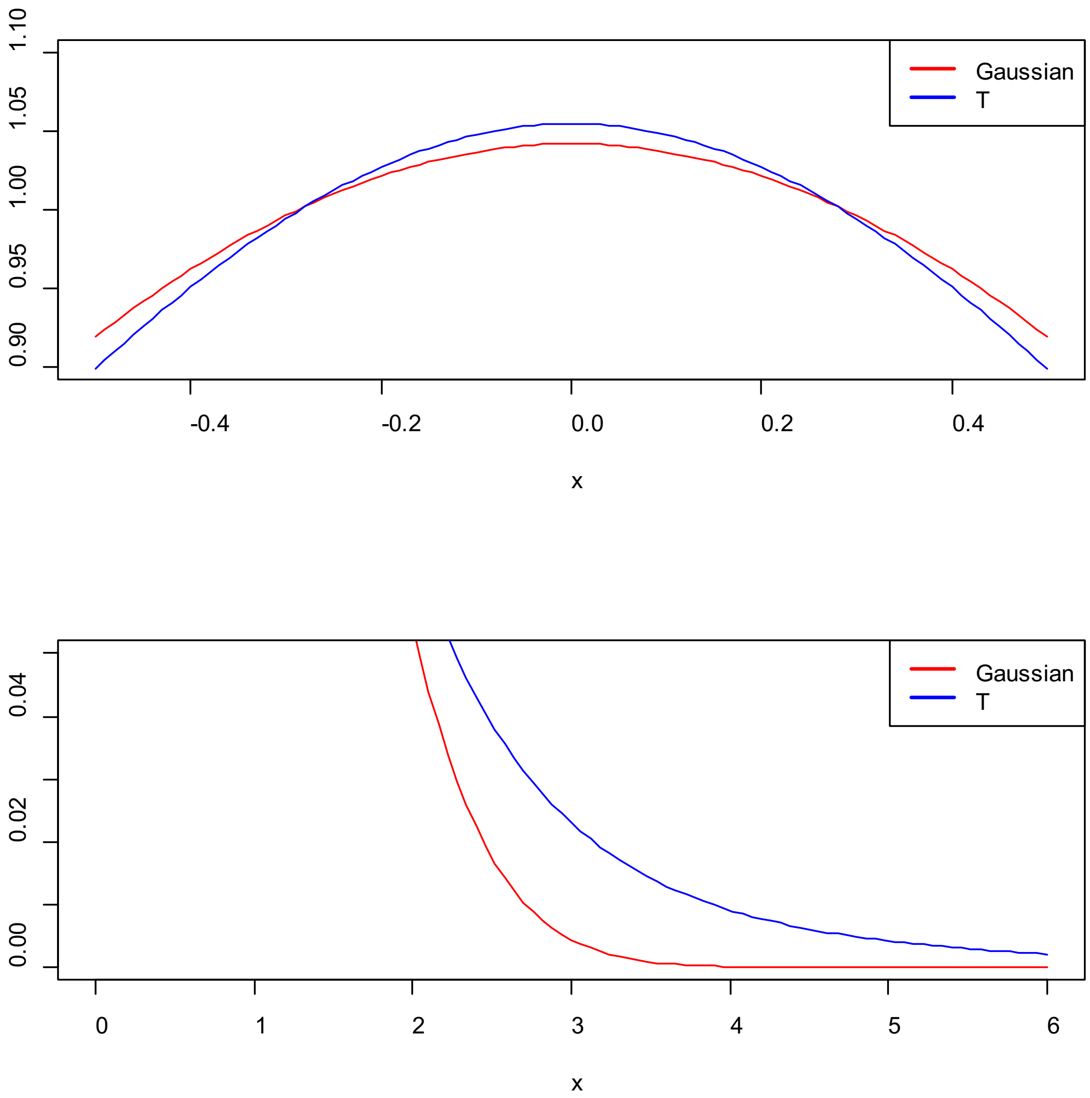


Figure 30. Visual comparison of the distributional characteristics of the Gaussian versus Student distribution.

2.3.13.5 Summary of the model for Bayesian parameter estimation

The specified model describes the data with five parameters: $< \mu_1, \mu_2, \sigma_1, \sigma_2, \nu >$. The priors were very vaguely defined. Noncommittal priors have the advantage that the parameter estimates are primarily determined by the empirical data (viz., bottom-up/data driven inference) and not by *a priori* theoretical considerations which might bias the model if inaccurate. The analysis willthus produce five parameter estimates that are statistically plausible given the experimental data at hand.

We parametrised the model with default (noninformative priors) as defined in the "BEST" R package (Kruschke & Meredith, 2012), specifically we defined normal priors with a large minimally informative standard deviation for μ, uniform minimally informative priors for σ, and an minimally informative exponential prior for *ν*. Mathematical details about this specification are provided in chapter 11 and 12 in Kruschke (2015).

First, we obtained exact Bayesian estimates for the parameters of interest. We ran the Metropolis-within-Gibbs sampler with 3 chains, 500 adapt steps (to "tune" the sampler), 1000 burn-in steps[132] and 100000 iterations. We did not use any thinning as this is not a recommended technique to avoid autocorrelation when sufficient time/computational resources are available (2013).

2.3.13.6 Markov chain Monte Carlo simulation output analysis and convergence diagnostics for experimental conditions V_{00} and V_{10}

As mentioned previously, there are currently no official guidelines for reporting Bayesian analysis in psychology (Kruschke, 2015). This lack of formal conventions also holds true for Markov Chain Monte Carlo methods.[133] However, it has been recommended that convergence diagnostics should be carefully examined and explicitly

[132] The general (though questionable) justifications for burning the initial (supposedly invalid) samples is based on the intention to give the Markov Chain enough time to stabilize to the stationary distribution π (cf. Meyn & Tweedie, 1993). Using a "random" seed is another alternative to burn-in for choosing an unbiased starting point.
[133] For a remedial attempt concerning the reporting of Monte Carlo methods in structural equation modelling see Boomsma (2013).

reported (Martyn et al., 2016). Given that MCMC sampling forms the basis for the posterior distribution (which in turn forms the basis for subsequent Bayesian probabilistic inference) we followed these sensible recommendations and report several (qualitative and quantitative) diagnostic criteria of convergence. For this purpose, we utilised the "`Coda`" package (2004) in R which provides essential functions for monitoring, summarizing, and plotting the output from iterative MCMC simulations. A visual summary for experimental condition V_{00} is provided in Figure 31 and various convergence diagnostics will be briefly discussed in the subsequent paragraphs.

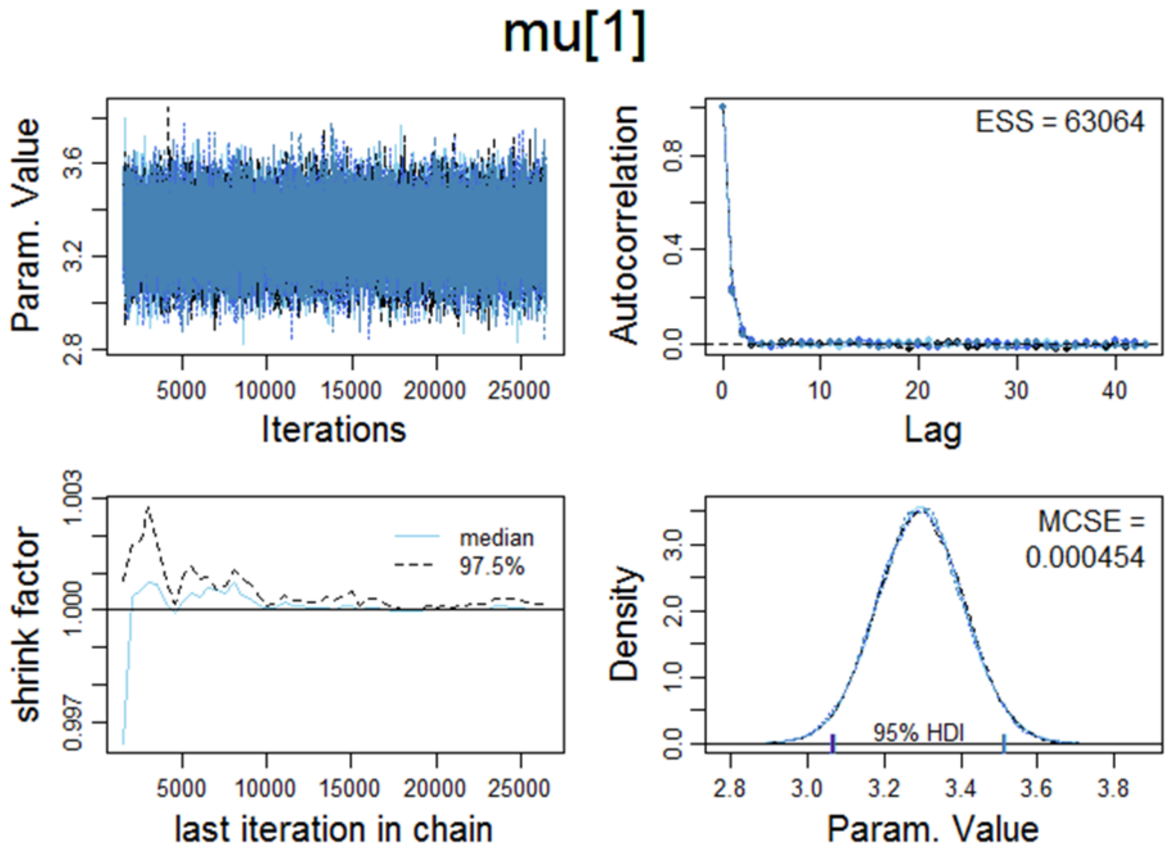


Figure 31. Visualisation of various MCMC convergence diagnostics for μ_1 (corresponding to experimental condition V_{00}).

Trace plot: In order to examine the representativeness of the MCMC samples, we first visually examined the trajectory of the chains. The trace plot (upper left panel of Figure

31) indicates convergence on θ, i.e., the trace plot appears to be stationary because its mean and variance are not changing as a function of time. Moreover, the mixing time of the Markov chain looks satisfactory as the Markov chain appears to rapidly approximate its steady state distribution.

Density plot: The density plot (lower right panel of Figure 31) consists of a smoothed (averaged) probability density function. Moreover, the plot entails the 95% HDI and it displays the numerical value of the Monte Carlo Standard Error (MCSE) of 0.000454. The Monte Carlo Error (MCSE) is the uncertainty which can be attributed to the fact that the number of simulation draws is always finite. In other words, it provides a quantitative index that represents the quality of parameter estimates. For more information on the Markov chain central limit theorem see Jones (James Flegal, Hughes, Vats, Dai, & Dootika Vats, 2017). The MCSE package in R provides convenient tools for computing Monte Carlo standard errors and the effective sample size (Gelman et al., 2004). Notice that relatively small MCSEs indicate high estimation precision level. The main idea is to terminate the simulation when an estimate is sufficiently accurate for the scientific purpose of the analysis. The MCSE at hand is more than adequate for the purpose at hand. Many practitioners utilize quantitative convergence diagnostics like the MCSE in addition to visual inspections of trace-plots to evaluate if the chain has been run long enough.

Shrink factor: Another quantitative metric to check convergence is the shrink factor, a.k.a. Brooks-Gelman-Rubin statistic (Kruschke, 2014) or "potential scale reduction factor" denoted with $\hat{R}$ (left lower panel). $\hat{R} = 1$ indicates that the chain is fully converged. As a heuristic "rule-of -thumb" $\hat{R} > 1.1$ indicates that the chains may not have converged adequality and additional tests should be carried out (Kass, Carlin, Gelman, & Neal, 1998). The mathematical basis of $\hat{R}$ (based on the between chain variability) can become complex and is not important for the context at hand. Theoretically, the larger the number of iterations T, the closer $\hat{R}$ should approximate 1, i.e., $\mathrm{T} \rightarrow \infty, \hat{R} \rightarrow 1$. It can be seen in Table 7 that $\hat{R} \approx 1$. That is, the qualitatively presupposed convergence is quantitatively corroborated.

The upper right panel of Figure 31 shows the diagnostics for *autocorrelation*. Autocorrelation is a quantitative measure of how much independent information is contained within a Markov chain. If autocorrelation is high the amount of information conveyed by each sample is reduced. Consequently, the sample is not representative of the posterior distribution[134]. Autocorrelation within a chain is the correlation of a value with subsequent values *k* steps ahead (Gelman et al., 2004). To quantify autocorrelation, a copy of the chain is superimposed on its original and the correlations are computed. The number of steps between the original chain and its copy is termed *lag*. Hence, the autocorrelation can be calculated for any arbitrary lag value (or a range of lags). As can be seen in Figure 31 the autocorrelation function drops steeply around $lag_{(k)} < 3$ which indicates a low autocorrelation. The *effective sample size* (EES) of a Markov chain is a function of the autocorrelation and hence a metric of information. The ESS was introduced by (Friendly, Monette, & Fox, 2013) is based on the proportion of the actual sample size to the amount of autocorrelation. The EES can be utilized to determine whether the number of Monte Carlo samples is sufficient to produce an accurate posterior distribution. The MCMC at hand is based on a larger sample

[134] One way to counteract MCMC autocorrelation is "thinning" of the Markov Chain. However, this is not a recommended technique because valuable information is lost which could negatively impact the accuracy of the estimation of the posterior distribution. A preferable strategy is to produce longer Markov chains instead.

(120000) than the estimated EES of 63064 and we are thus content with this numerical indicator.

We examined the convergence diagnostics for all other parameters (see Appendix B24 for details), all of which suggested that the desired equilibrium distribution π had been reached as can be seen in Table 7. Note that 'Rhat' is the potential scale reduction factor (at convergence, Rhat=1) and 'n.eff' is a crude measure of effective sample size.

Table 7

Summary of selected convergence diagnostics for μ_1, μ_2, σ_1, σ_2, and v.

	Rhat	n.eff
mu1	1	61124
mu2	1	63411
nu	1	22851
sigma1	1	50537
sigma2	1	46096

Note. Because we conducted the analysis multiple times results might vary slightly due to randomness in the Markov chains.

In sum, the results of our MCMC diagnostic analysis were satisfactory and support the notion that the stationary distribution is the correct one for *a posteriori* sampling purposes. It should be emphasised that no method can conclusively prove convergence (Plummer, 2003, 2005), that is, it can only be falsified in the Popperian sense. None of the test batteries discussed above can conclusively “prove” that the MCMC approach has provided reliable estimates of posterior characteristics. However, we utilised a diverse battery of MCMC convergence tests and the convergence diagnostics uniformly suggest convergence to the equilibrium distribution of the Markov chain for all model parameters (additional diagnostics are reported in Appendix B25 and Appendix B26).

Therefore, we proceed with the analysis of the posterior distribution which is described in the next subsection.

2.3.13.7 Bayesian MCMC parameter estimation for condition V_{00} and V_{10}

Next, we inspected the results of the Bayesian MCMC parameter estimation for condition V_{00} and V_{10}. The correlation matrix for all parameters of interest is given in Figure 32 and the posterior distributions of μ_1 and μ_2 with associated 95% posterior high density credible intervals is are depicted in Figure 33. The posterior distributions of σ_1 and σ_2 and the Gaussianity parameter ν with associated 95% posterior high density credible intervals is visualised in Figure 35. The ROPE and HDI-based decision algorithm is explained in Appendix B22.

Table 8

Results of Bayesian MCMC parameter estimation for experimental conditions V_{00} and V_{10} with associated 95% posterior high density credible intervals.

	mean	median	mode	HDI%	HDIlo	HDIup	compVal	%>compVal
mu1	3.2939	3.2940	3.2869	95	3.073	3.524		
mu2	3.7102	3.7103	3.7215	95	3.507	3.917		
muDiff	-0.4163	-0.4170	-0.4320	95	-0.722	-0.111	0	0.369
sigma1	0.9970	0.9923	0.9835	95	0.836	1.173		
sigma2	0.9132	0.9091	0.9054	95	0.761	1.071		
sigmaDiff	0.0838	0.0834	0.0896	95	-0.139	0.309	0	77.197
nu	43.2890	34.9173	18.8500	95	5.046	105.167		
log10nu	1.5356	1.5430	1.5465	95	0.952	2.105		

```
effSz      -0.4363 -0.4365 -0.4338   95 -0.759  -0.115        0      0.36
9
```

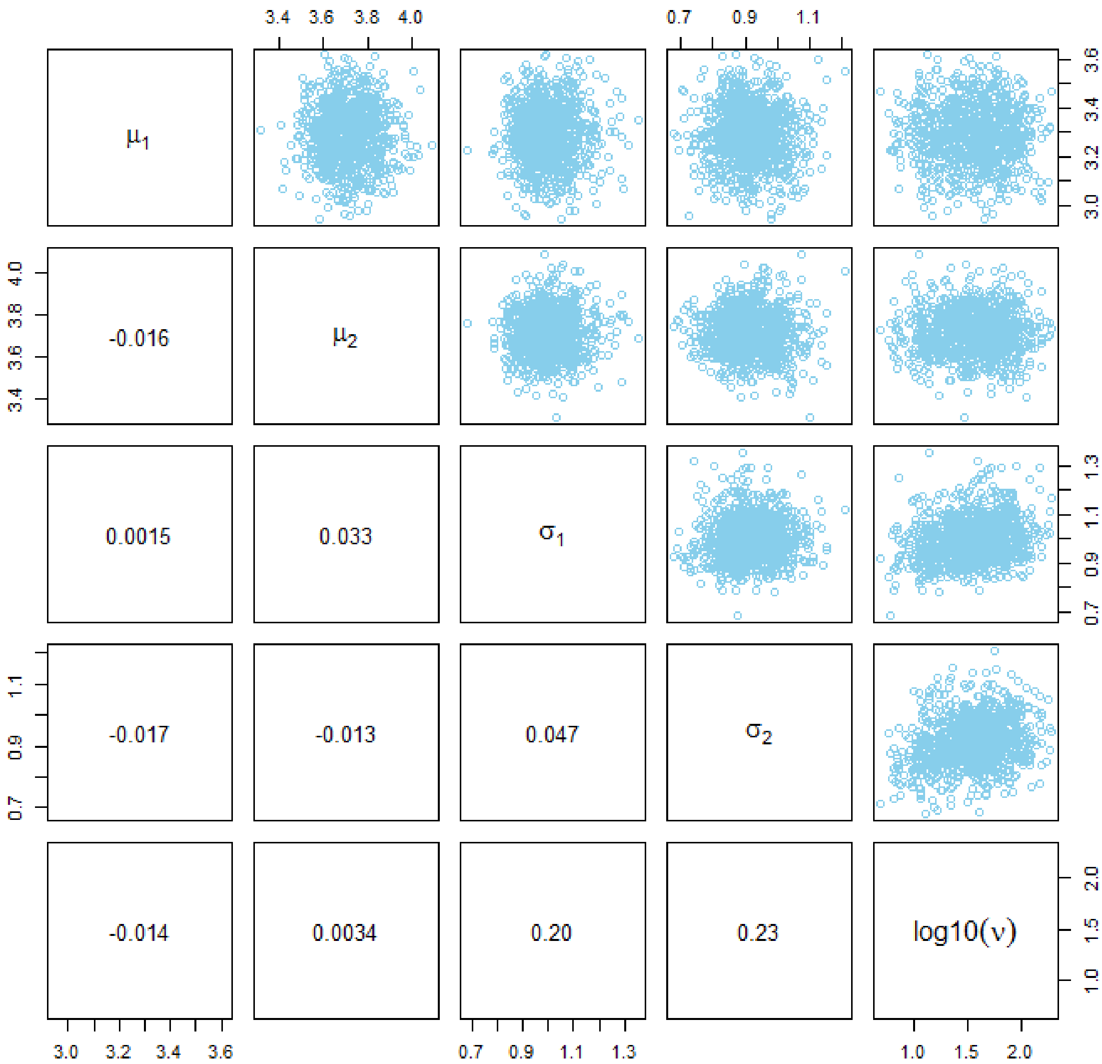


Figure 32. Correlation matrix for the estimated parameters (μ_1, μ_2, σ_1, σ_1, ν) for experimental condition V_{00} and V_{10}.

A high-resolution vector graphic is available under the following URL as a PDF: http://irrational-decisions.com/phd-thesis/cor-matrix-exp1.pdf

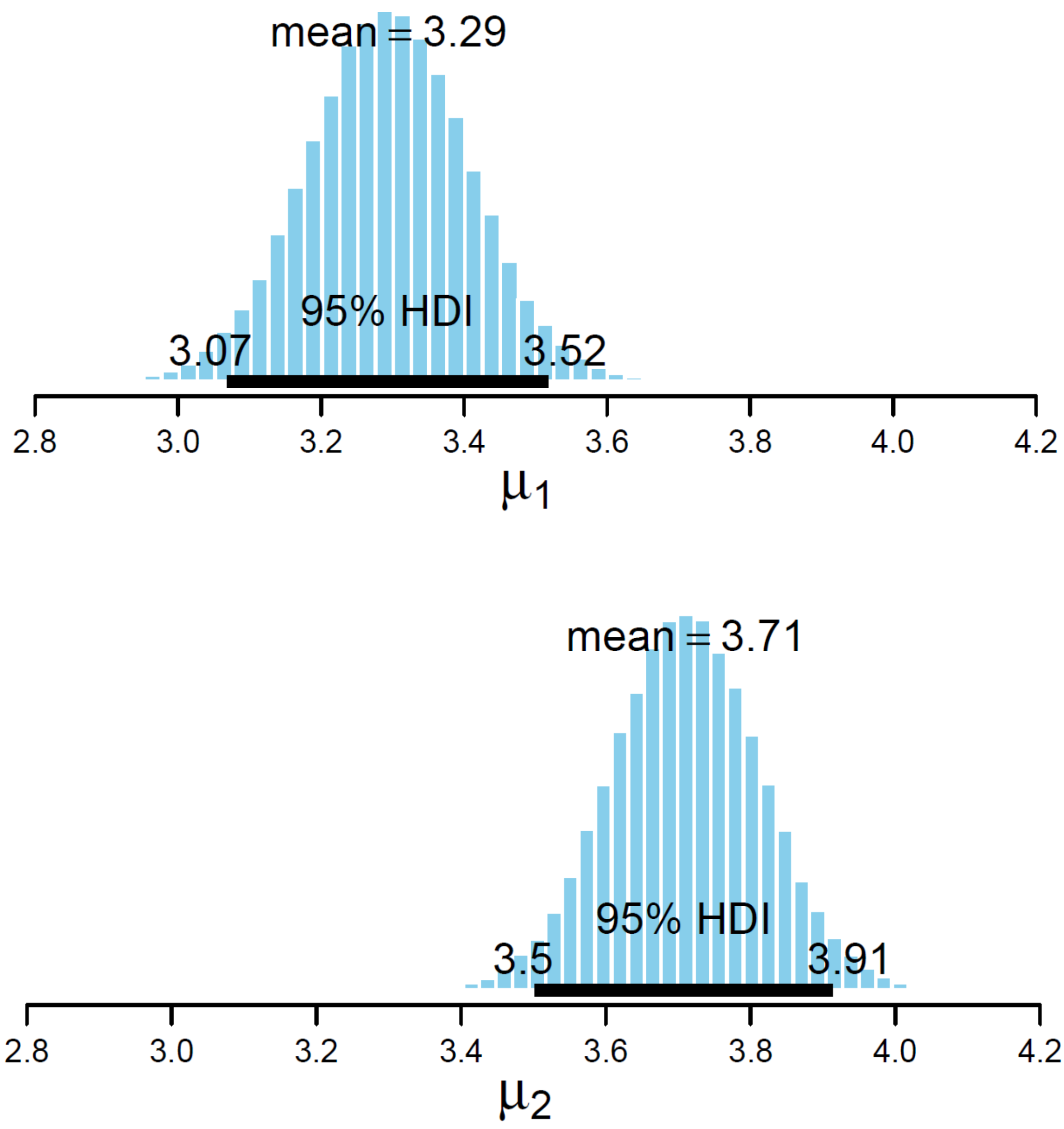
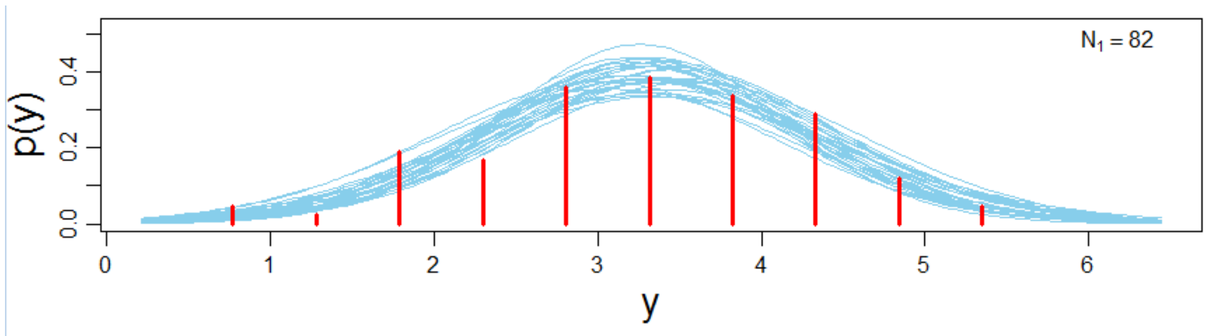


Figure 33. Posterior distributions of μ_1 (condition V_{00}, upper panel) and μ_2 (condition V_{10}, lower panel) with associated 95% posterior high density credible intervals.



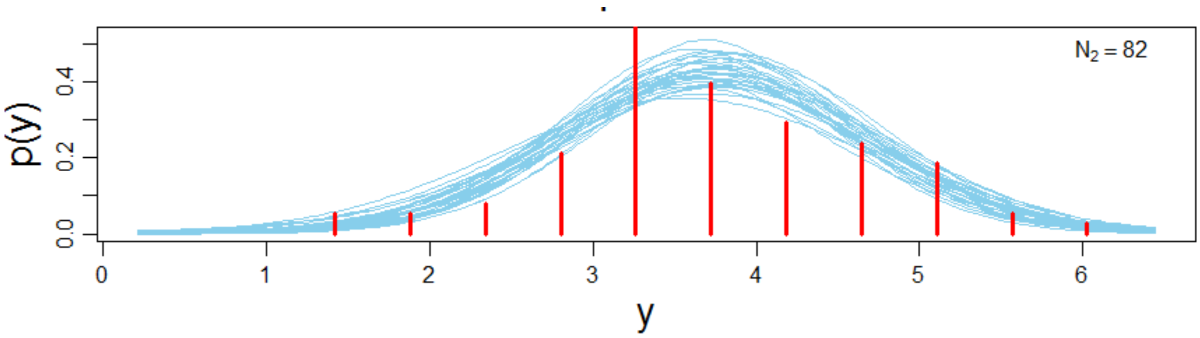


Figure 34. Randomly selected posterior predictive plots (n = 30) superimposed on the histogram of the experimental data (upper panel: condition V_{00}; lower panel condition V_{10}).

Figure 36 shows the plot for the "posterior predictive check". The graphic depicts curves that were produced by selecting random steps in the MCMC chain and plotting the t distribution (with the corresponding values of μ, σ and ν for that step). In total n = 30 representative t-distributions are superimposed on the histogram of the actual empirical dataset. The upper panel of

Figure 36 corresponds to condition V_{00} (μ_1) and the lower panel to the samples for condition V_{10} (μ_2). This combinatorial graphic thus allows to visually inspect if the model has a good fit with the experimental data. It can be seen that the specified model provides an accurate approximation for the centrality parameters of interest, i.e., the "goodness-of-fit" is heuristically satisfactory as there is little discrepancy between the estimated values and the empirical data.

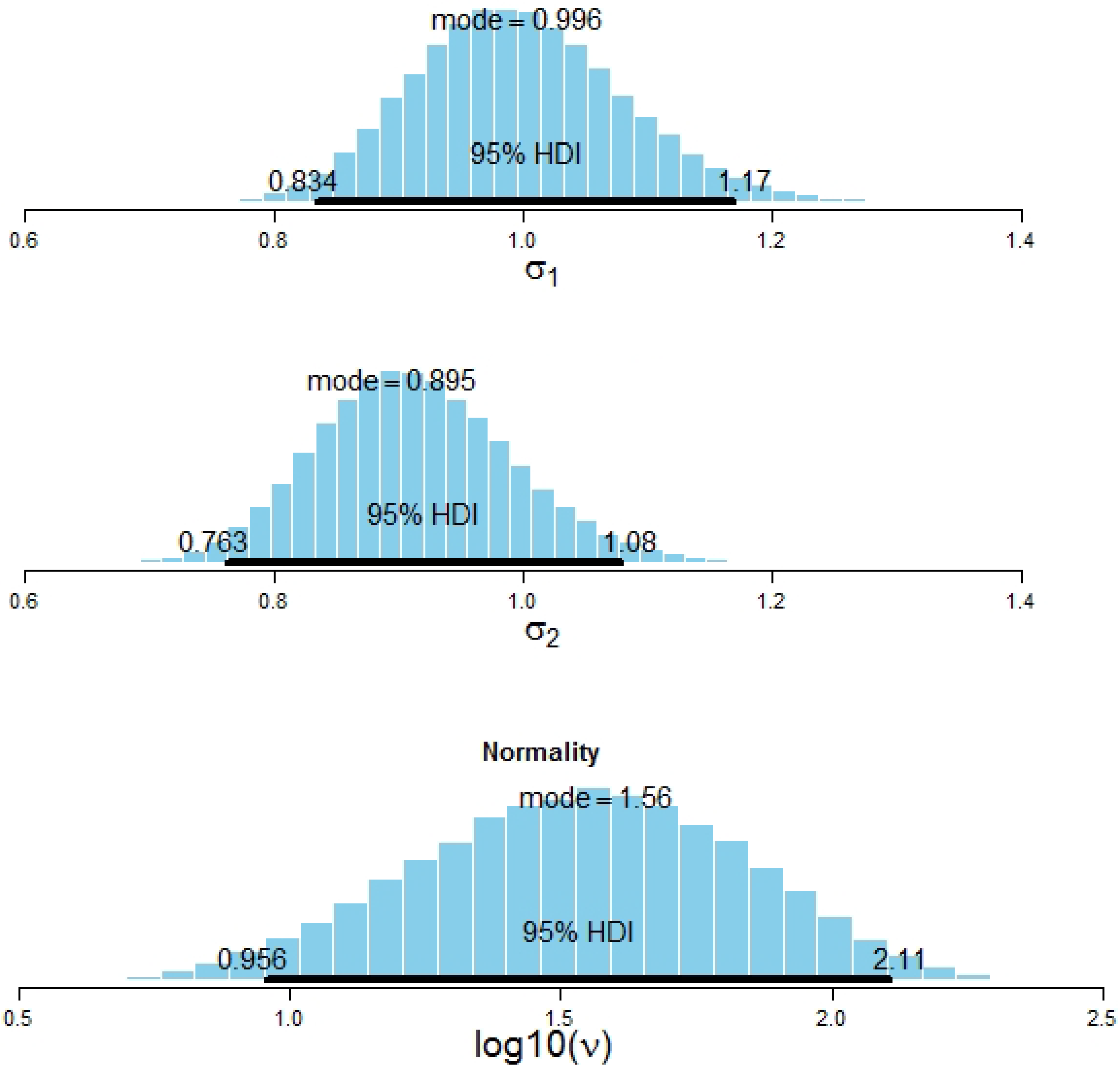


Figure 35. Posterior distributions of σ_1 (condition V_{00}, upper panel), σ_2 (condition V_{10}, lower panel), and the Gaussianity parameter ν with associated 95% high density intervals.

2.3.13.8 Bayesian MCMC parameter estimation for the mean difference between condition V_{00} and V_{10}

After obtaining exact posterior estimates for all parameters, we modelled the mean difference between condition V_{00} and V_{01}. For this purpose, we ran another MCMC simulation with 100000 iterations, 500 adaptation steps, and 1000 burn-in steps. We did not apply any thinning to the Markov chain and ran multiple chains in parallel (with the exploitation of multi-core CPUs). A visual summary of the posterior distribution of the estimated difference between means is provided in Figure 36

Figure 36. The posterior predictive plot indicated a good fit (as illustrated in Figure 37). We prespecified a ROPE centred around zero with a radius of 0.1. As can be seen in Figure 36, the ROPE did not overlap with the 95% HDI. Thus, we concluded that the credible difference between mean is unequal to zero and we rejected H_0 based on this decision algorithm. We also examined the credible range of the effect size associated effect size and constructed a ROPE ranging from [-0.1, 0.1] arounds its null value. Again, the ROPE did not overlap with the HDI. In addition, we modelled the standard deviation of the difference between means which resulted in an estimated value of ≈ 1.22 (95% HDI ranging from [1.01, 1.43]). A numerical summary of the results is given in Table 9. A complete high-resolution synopsis can be accessed under the following URL: http://irrational-decisions.com/phd-thesis/summary-exp1-cond-v00-vs-v10.pdf

Based on this analysis, we concluded that the credible difference between mean is ≈ -0.43 with a 95% HDI ranging from [-0.70, -0.15]. The associated effect size was estimated to be ≈ -0.36 and the associated 95% HDI spanned [-0.56 -0.12]. We utilised the 95% HDI in combination with a predefined ROPE in order to make a dichotomous decision concerning our a priori hypothesis. The results cross-validated those obtained in our previous analyses and provided additional valuable information about the empirical data at hand which was unavailable in the NHST and Bayes Factor framework, thereby significantly increasing the precision of our statistical inferences.

Table 9

Numerical summary of the Bayesian parameter estimation for the difference between *means for experimental condition V_{00} vs. V_{01} with associated 95% posterior high density credible intervals.*

	mean	median	mode	HDI%	HDIlo	HDIup	compVal	%>compVal
mu	-0.427	-0.426	-0.425	95	-0.703	-0.150	0	0.138
sigma	1.218	1.214	1.201	95	1.013	1.435		
nu	40.629	32.475	16.432	95	3.368	101.342		
log10nu	1.494	1.512	1.553	95	0.835	2.092		
effSz	-0.353	-0.353	-0.357	95	-0.592	-0.118	0	0.138

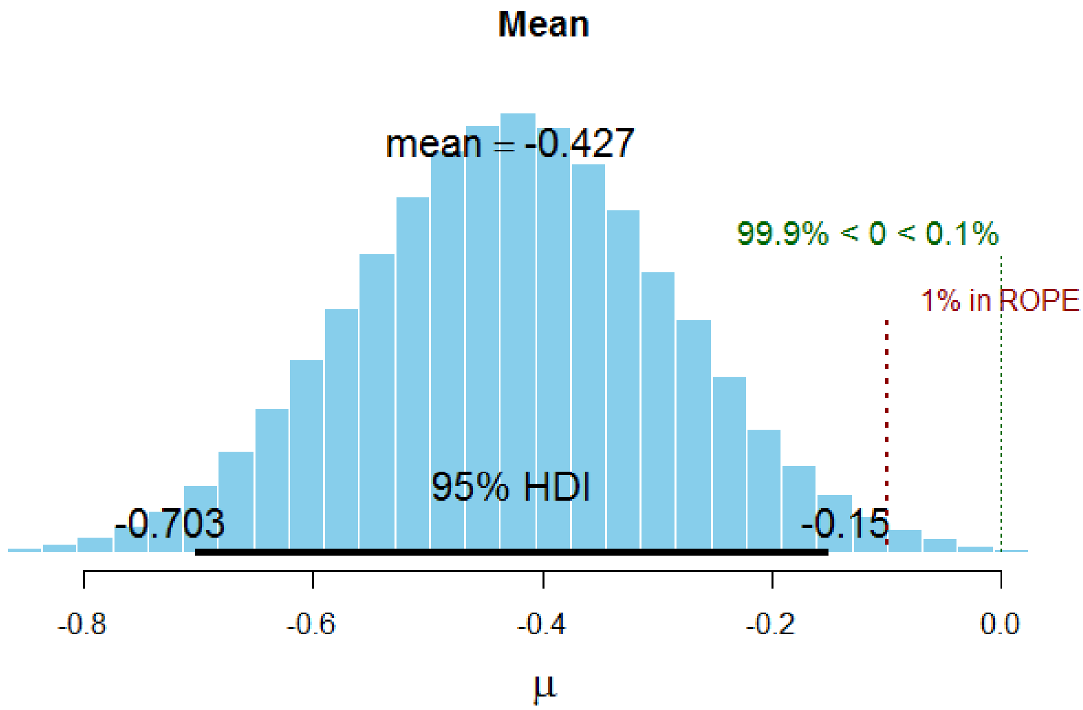


Figure 36. Visual summary of the Bayesian parameter estimation for the difference between means for experimental condition V_{00} vs. V_{01} with associated 95% HDI and a ROPE ranging from [-0.1, 0.1].

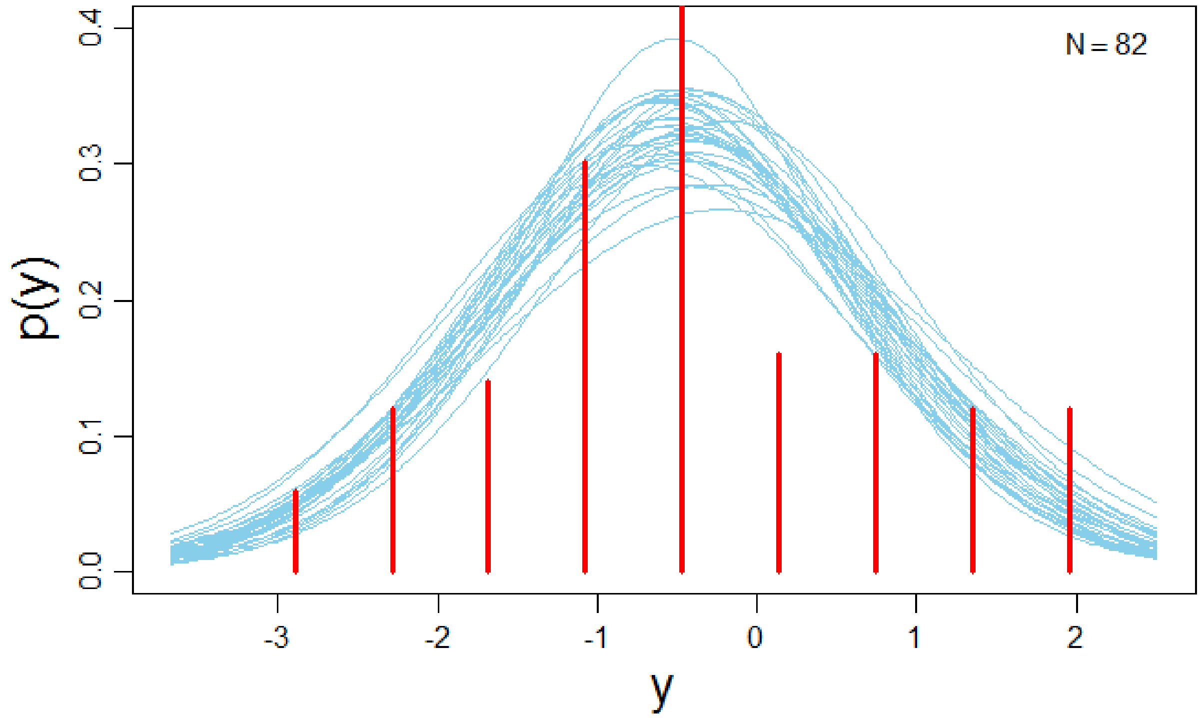


Figure 37. Posterior predictive plot (n=30) for the mean difference between experimental condition V_{00} vs. V_{01}.

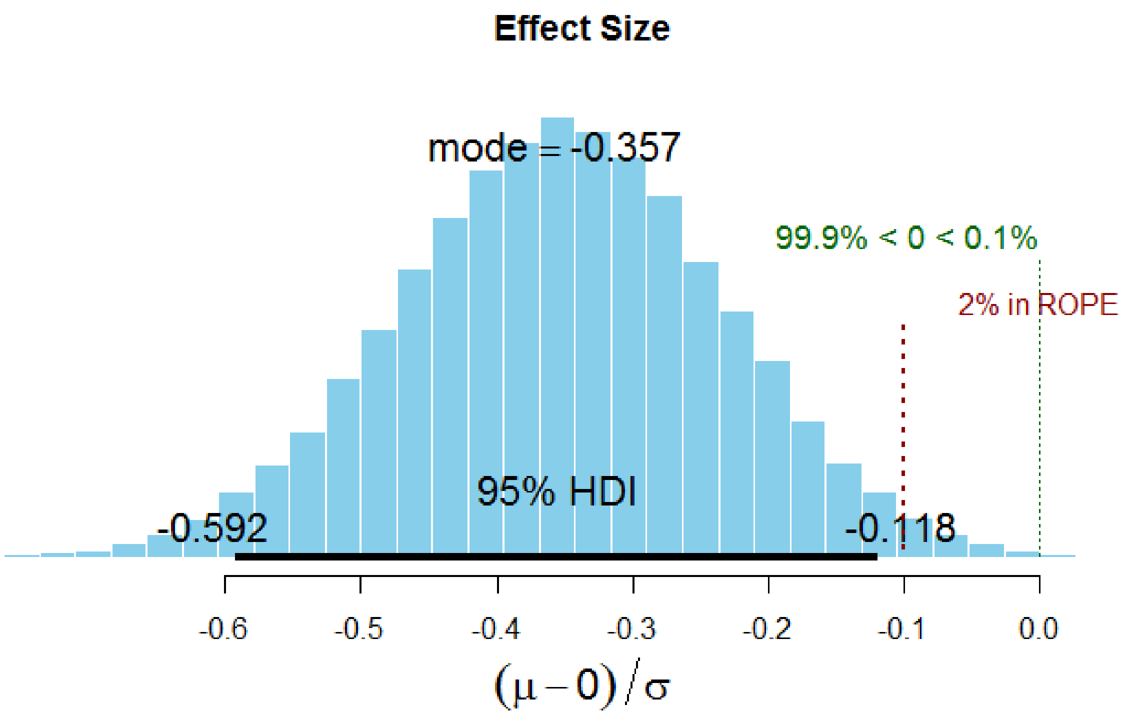


Figure 38. Visual summary of the Bayesian parameter estimation for the effect size of the difference between means for experimental condition V_{00} vs. V_{01} with associated 95% HDI and a ROPE ranging from [-0.1, 0.1].

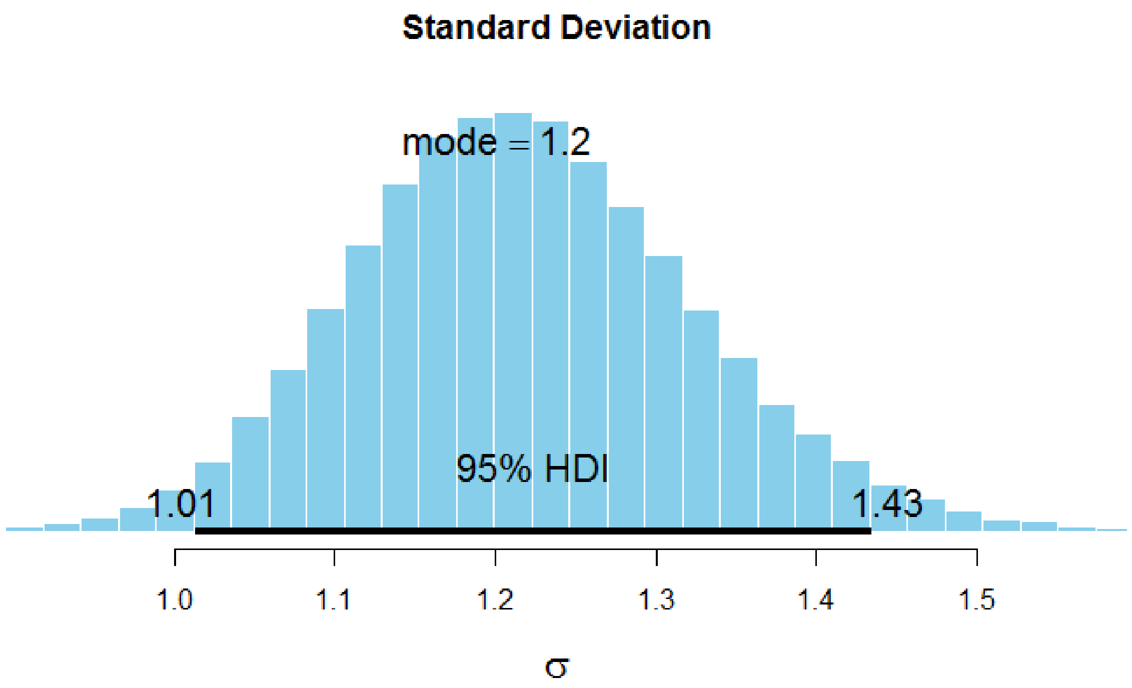


Figure 39. Visual summary of the Bayesian parameter estimation for the standard deviation of the difference between means for experimental condition V_{00} vs. V_{01} with associated 95% HDI and a ROPE ranging from [-0.1, 0.1].

2.3.13.9 Markov chain Monte Carlo simulation output analysis and convergence diagnostics for experimental conditions V_{01} and V_{11}

Next, we focused on the difference between experimental conditions V_{01} and V_{11}. For reasons of brevity, we do not report the individual parameter estimates and focus immediately on the difference between means in order to evaluate our hypothesis.

We thus proceed with our analysis of the difference between means of condition V_{01} and V_{11}. We ran the MCMC simulation with the same specification as reported before (burn-in=1000, adaptation=500, iterations=100000). The convergence diagnostics indicated that the equilibrium distribution π had been reached. The estimated mean difference between experimental conditions V_{01} and V_{11} was ≈ 0.54 with an associated HDI ranging from [0.23, 0.84]. The a priori constructed ROPE [-0.1, 0.1] did not overlap with the 95% HDI, thereby corroborating our initial hypothesis (i.e., based on this decision procedure H_0 can be rejected and H_1 is accepted). The associated effect size was estimated to be ≈ 0.41 (95% HDI ranging from [0.16, 0.65]) and the ROPE confirmed the (idiosyncratic) practical significance of this value. The results are summarised in numerical form in Table 10. A visual synopsis is illustrated in Figure 40.

Table 10

Numerical summary of the Bayesian parameter estimation for the difference between means for experimental condition V_{10} vs. V_{11} with associated 95% posterior high density credible intervals.

	mean	median	mode	HDI%	HDIlo	HDIup	compVal	%>compVal
mu	0.537	0.537	0.532	95	0.227	0.839	0	100
sigma	1.338	1.336	1.347	95	1.073	1.606		
nu	32.035	23.196	9.339	95	2.080	89.091		
log10nu	1.356	1.365	1.438	95	0.638	2.037		
effSz	0.406	0.404	0.406	95	0.164	0.654	0	100

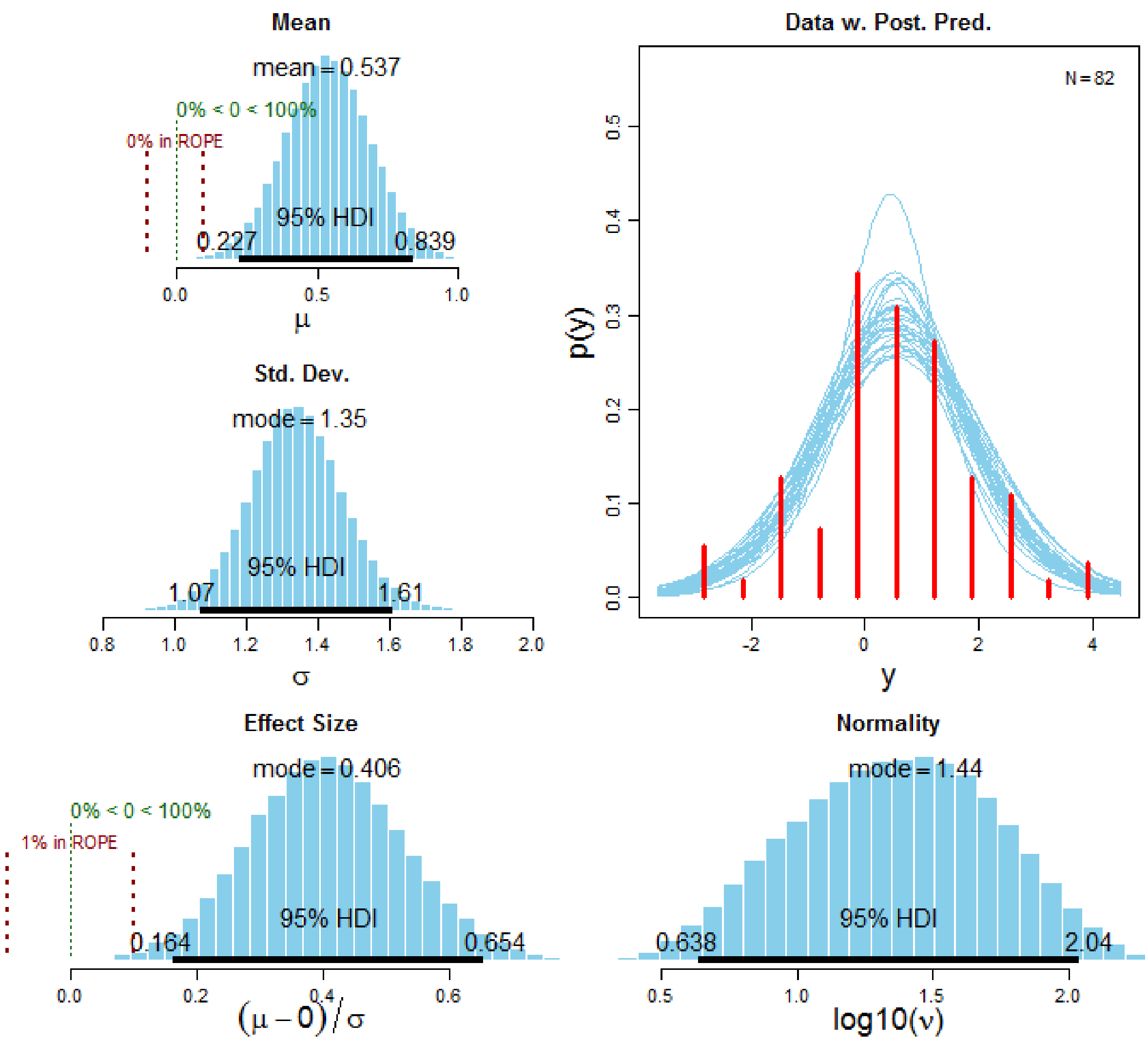


Figure 40. Visual summary of the Bayesian parameter estimation for the difference between means for experimental condition V_{10} vs. V_{11} with associated 95% HDIs and a ROPEs ranging from [-0.1, 0.1].

2.4 Discussion

The results of this experiment confirmed our *a priori* predictions and demonstrate noncommutativity effects in psychophysical visual judgments. Moreover, they are in line with the general predictions formulated by Atmanspacher and colleagues (Atmanspacher, 2014, 2016; Atmanspacher & Römer, 2012b). *Prima vista*, the observed noncommutativity effects might seem “irrational” but only if the results are analysed in isolation. However, if the results are conditionalized on the entire contextual situatedness of the experiment, the results make sense. Any type of measurement, (be it physical, psychological, or psychophysical) is always embedded in a specific context and this context significantly influences the measurement in question. It follows that measurements should never be considered in isolation. This holistic conceptualisation of scientific measurements is congruent with Nils Bohr’s Copenhagen interpretation of quantum mechanics (Filliben, 1975). Moreover, the Kolmogorovian notion of sample space assumes a single sample space for the entire universe. It should be emphasised that Kolmogorov himself did not defend this notion. In quantum mechanics, sample spaces are modelled as *n*-dimensional (compatible/incompatible) Hilbert spaces. This multidimensionality allows to incorporate results which appear paradoxical (irrational) in a unidimensional sample space (but see Busemeyer & Bruza, 2012). In sum, our results support the prediction that “non-commuting operations must be expected to be the rule rather than the exception for operations on mental systems” (Atmanspacher, 2014a, p. 24). To our best knowledge, the present psychophysics experiment is the first systematic investigation of noncommutativity in sequential visual perceptual judgments. The present data can be integrated into a progressively accumulating corpus of scientific literature which empirically illustrates that quintessential quantum mechanical principles like superposition, complementarity, and entanglement are applicable beyond the physical micro domain (Atmanspacher, 2012; Atmanspacher & Filk, 2013; Atmanspacher & Römer, 2012; beim Graben, 2013; Blutner et al., 2013; Busemeyer et al., 2011a; Kvam, Pleskac, Yu, & Busemeyer, 2015; Z. Wang et al., 2013). Our findings particularly highlight the importance of non-commutative structures in the measurement of psychophysical observables (cf. Atmanspacher, 2016).

Specifically, the data indicates that low luminance stimuli were on average rated significantly lower when anteceded by equivalent stimuli, relative to low luminance stimuli anteceded by high luminance stimuli (M_{Δ}=-0.42). On the other hand, the brightness of high luminance stimuli was on average rated significantly higher when the high luminance stimuli were anteceded by low luminance stimuli relative to high luminance stimuli anteceded by equivalent stimuli (M_{Δ}=-0.53). In the current experimental context, the most relevant difference between classical and quantum probability models is the way in which they deal with violations of the commutativity axiom (see Atmanspacher, 2014a). That is, the quantum model allows for violations of symmetry because observables do not have to commute. In other terms, the defining difference between classical probability theory and quantum probability theory is noncommutativity of cognitive operators. If projectors do commute, classical Kolmogorovian/Boolean probability theory applies, "iff" (if and only if) they do not commute, quantum probability applies. Consequently, the present results can be parsimoniously accounted for in the quantum framework whereas classical cognitive models have to utilise (non-parsimonious) auxiliary hypotheses to explain the results *post festum* (see Discussion section 6.2 for a more elaborate version of this argument in the context of the Duhem-Quine Thesis). Furthermore, the quantum model makes the prediction (noncommutativity of cognitive operations) *a priori* (an important aspect of hypothesis testing which allows for prespecified planned *post-hoc* comparisions) as noncommutativity is a defining feature of this explanatory framework. Indeed, is has been argued that noncommutative operations are ubiquitous in psychology and related areas (Atmanspacher, 2014a; Atmanspacher & Filk, 2013; Atmanspacher & Römer, 2012; beim Graben, 2013). Our results are thus commensurate with those discussed in the previous section (i.e., section 1.12) and can be interpreted as a QQ-equality because the psychophysical results display the same ordering schema as the Gallup poll described before (viz., "Clinton followed by Al Gore" versus "Al Gore followed by Clinton). As discussed before, classical probability theory cannot easily account for this kind of order effects because events are represented as sets and are stipulated to be commutative, that is, $P(A \cap B) = P(B \cap A)$. The data of Experiment 1 thus violates the Kolmogorovian commutativity axiom which is central to the majority of cognitive/computation models. Quantum models of cognition can thus parsimoniously account for these *prima facie* "irrational/paradoxical" judgment and decision-making phenomena and indeed predicts them *a priori*. The current experiment thus provides corroborating empirical evidence for the validity of the predictions derived from the quantum model.

CHAPTER 3. EXPERIMENT #2: CONSTRUCTIVE MEASUREMENT EFFECTS IN SEQUENTIAL VISUAL PERCEPTUAL JUDGMENTS

3.1 Experimental purpose

Our previous experiment provided empirical support for the QP prediction that sequential introspective psychophysical judgments are noncommutative (cf. Atmanspacher, 2014a; Z. Wang et al., 2014). However, the experimental design left some important questions unresolved. Specifically, one outstanding empirical question in relation to the previous analysis is the following: Does the mere act of performing a psychophysical measurement have a constructive effect which influences subsequent psychophysical measurements? Recent empirical research in the domain of affective

(White et al., 2014b) and attitudinal judgments (White et al., 2015) suggests that this is the case. As discussed before, conceptually related results have also been reported in various other domains (e.g., Trueblood & Busemeyer, 2011; Z. Wang & Busemeyer, 2013; Z. Wang et al., 2014).

Based on this theoretical and empirical background, we formulated several *a priori* hypotheses concerning the constructive role of psychophysical measurements. Specifically, we were interested to experimentally test whether providing a psychophysical judgement for a high vs. low luminance visual stimulus exerts a constructive influence on a subsequent psychophysical judgment of an oppositely valued visual stimulus.

An additional objective of the present experiment was to conceptually replicate and cross-validate the previously discussed results reported by White et al. (2014b, 2015) in a completely different context. Given that affective and attitudinal evaluation are higher-order cognitive processes, we employed a more controlled experimental approach in order to establish the robustness of the QP principles at a more fundamental perceptual level. The main advantage of a low-level psychophysical approach is that differences in visual stimulus intensity can be varied quantitatively in a much more controlled and systematic fashion (as compared to the compound stimuli used in the experiments by White et al., 2014b; 2015). Another methodological/statistical advantage of the psychophysics approach towards noncommutativity is that it provides a significantly larger dataset because psychophysical measurements can be recorded in rapid succession. Moreover, science possesses much more detailed knowledge about the workings of the perceptual systems, as compared to the much more complex higher-order cognitive processes which are thought to underpin affective and attitudinal judgments. Therefore, we approached the question of whether judgments exert constructive effects in psychological measurements from a more reductionist psychophysical point of view. From a reductionist point of view, research should progress in an incremental manner – starting at the most fundamental level and gradually move up to more complex systems. Once an empirical foundation has been firmly established at a low level one can subsequently move up to the next level in the cognitive processing hierarchy to explore more complicated compound higher-level cognitive processes. For this purpose, we designed a psychophysics laboratory task in order to isolate and empirically investigate the psychophysical mechanism of interest.

3.2 A priori hypotheses

Our hypotheses were formulated *a priori* and they were derived from the pertinent quantum cognition literature (Atmanspacher, 2014a, 2016; Atmanspacher & Römer, 2012; Z. Wang et al., 2013; White et al., 2015; White, Pothos, & Busemeyer, 2014a). The experimental conditions in our design conceptually correspond to the positive vs. negative affective valence conditions in (White et al., 2014b)

The directional *a priori* hypotheses of primary interest were:

H_1: Measuring subjectively perceived brightness of a high luminance stimuli first (i.e., binary measurement condition) produces a decrease in subsequent psychophysical measurement of a low luminance stimuli as compared to the singular measurement condition.

H_2: Measuring the subjectively perceived brightness of a low luminance stimuli first produces an increase in the subsequent psychophysical measurement relative to the singular measurement condition.

In symbolic form the hypotheses can be expressed as follows:

H_1: $\mu_{V00} > \mu_{V01}$

H_2: $\mu_{V10} < \mu_{V11}$

where

V_{00} = high luminance stimuli → low luminance stimuli (singular measurement)

V_{01} = high luminance stimuli → low luminance stimuli (binary measurement)

V_{10} = low luminance stimuli → high luminance stimuli (singular measurement)

V_{11} = low luminance stimuli → high luminance stimuli (binary measurement)

Note that our prime objective was not to demonstrate noncommutativity in psychophysical judgments (this was the main purpose of Experiment 1). Rather, this experiment was designed to elucidate the potentially constructive influence of an intermediate psychophysical judgment on a subsequent one. Both hypotheses were logically derived from the predictions of the QP model (Pothos & Busemeyer, 2013).

3.3 Method

3.3.1 Participants and Design

The experiment was conducted in the psychology laboratory of the University of Plymouth (United Kingdom) and ethical approval was obtained from the universities human research ethics committee. Seventy psychology students from the University of Plymouth participated in this study (45 women and 25 men, ages ranging between 18 and 29 years, M_{age} = 21.79; SD_{age} = 4.54). Students were recruited via the cloud-based

Participant Management Software (Sona Experiment Management System®, Ltd., Tallinn, Estonia; http://www.sona-systems.com) which is hosted on the universities webserver. In addition, a custom-made website was designed in HTML to advertise the study in an attractive way to the student population (URL: http://irrational-decisions.com/sona/qp.html). All participants received course credit for their participation.

3.3.2 Apparatus and materials

The experiment was isomorphic to Experiment 1, except for a single experimental parameter, i.e., we systematically varied the presence or absence of intermediary psychophysical measurements in a counterbalanced manner (as described below).

3.3.3 Experimental Design

The basic structure of the experiment was a 2(measurement condition: singular rating vs. binary measurement) x 2(stimulus order: high luminance → low luminance vs. low luminance → high luminance) repeated measures factorial design as schematized in Figure 41. The dependent measure was the condition dependent brightness rating which was recorded on a visual analogue scale (VAS) (Aitken, 1969) identical to Experiment 1.

3.3.4 Experimental procedure

Before the commencement of the experiment, participants were briefed and accorded informed consent. Subsequently, participants were seated in front of a personal and received further instructions.

3.3.5 Sequential visual perception paradigm

Similar to Experiment 1, we first collected general demographic information. Then, the visual perception paradigm was initiated. Before the beginning of the experimental trials, participants completed a practice block consisting of 4 trials. During the practice phase, participants were acquainted with the workings of the VAS and the general experimental procedure. After that, the experimental block was automatically initiated. A single experimental trial consisted of the successive presentation of two stimuli. A pair of stimuli always consisted of opposing luminance levels, that is, low luminance was always followed by high luminance and vice versa. Each stimulus was presented for 60 frames (≈ 1 seconds)[135]. In 50% of the trials participants were requested to rate the brightness of the first stimulus (intermediate measurement) and subsequently the second rectangle (final measurement). In the remaining trials participants were presented with the first stimulus but were informed that no rating was required (singular measurement condition). After a manual response was emitted (single left mouse click), the second stimulus appeared which consistently required a VAS rating response. In other terms, the task of participants was to evaluate the visual stimuli under different instructional sets. Hence, for half of the trials participants were required to evaluate the brightness of both stimuli whereas for the other half they only had to judge the second stimuli. In the PsychoPy backend, trials were organised into two blocks. The first block contained the "intermediate (i.e., binary) measurement condition" and the second block the "no intermediate (i.e., singular) measurement condition". Both blocks were programmatically enclosed within a loop which enabled randomization of block

[135] Vertical refresh rate of screen = 60Hz.
1 frame = 1000ms/60 ≈ 16.67ms (frame to frame variability on average = 2.18ms)

presentation order. In addition, trial order within each block was randomized within participants. Randomization was archived by utilising the Python "NumPy" package (Van Der Walt et al., 2011) and its relevant randomization functions. The exact temporal sequence of events within each experimental trial is schematically depicted in Figure 41.

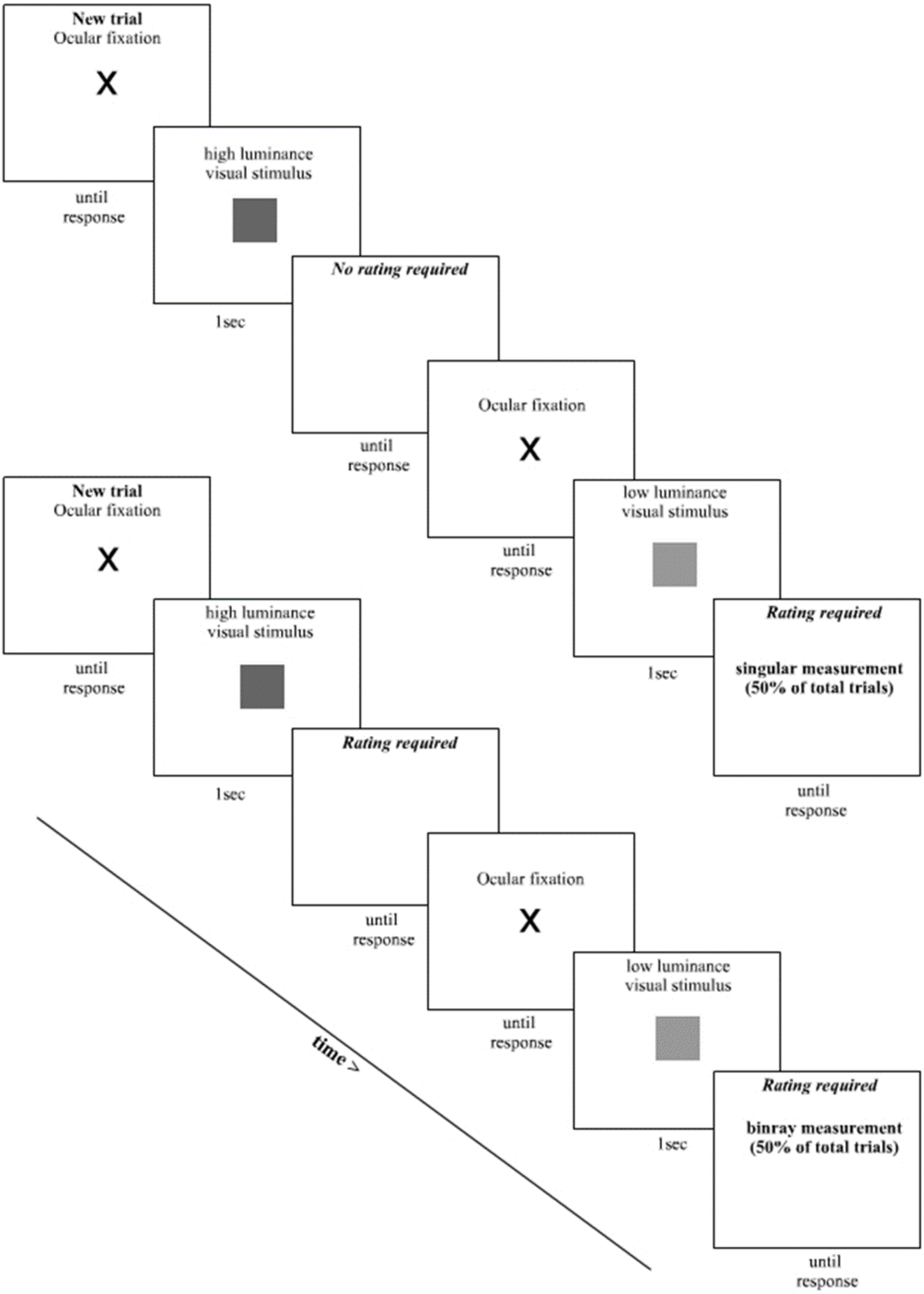


Figure 41. Schematic visualisation of the temporal sequence of events within two successive experimental trials.

The within-trial sequence of events was as follows: Initially, a white fixation cross was displayed on a black background until a manual response was emitted (single left mouse-click). The following instructions were presented to participants: "*New trial: Please fixate the cross with your eyes and click the mouse when you are ready*". Next, a rectangle of either high or low luminance appeared in the centre of the screen (screen size = 1920 x 1080, the application was executed in fullscreen mode) with a fixed duration of 120 frames. The rectangle was then replaced by either a rating request or no rating request, (i.e., singular vs. binary measurement condition) which was presented until a response was emitted (either a rating on the VAS or a mouse-click response, depending on the respective condition). After that, the second rectangle appeared for the same temporal duration followed by the final rating request. In sum, participants completed a total of 300 experimental trials.
Upon completion of the experiment, participants were debriefed and were given the possibility to ask questions concerning the purpose and theoretical background of the study. Finally, participants were thanked for their cognitive efforts and released.

3.4 Statistical Analysis

We utilised the same analyses as in the previous experiment, i.e., NHST analysis, Bayes Factor model comparison, and MCMC-based Bayesian parameter estimation. For reasons of parsimony and to avoid repetition, we refer to the preceding chapter for further details. As expounded above, the subsequent analyses exclusively focus on the postulated constructive role of psychophysical measurements (White et al., 2015, 2014b).

3.4.1 Frequentist NHST analysis

We first tested if the Gaussianity assumption which underpins parametric testing procedures was satisfied. We utilised the R package "`moments`"[136] to evaluate skewness[137] and kurtosis[138] of the sample distributions. Both distributional characteristics were within the normal range of ±2 and ±7, respectively (cf. Cain et al., 2016; Groeneveld & Meeden, 1984), indicating that the data is neither saliently skewed nor kurtotic. In addition, Shapiro-Wilk tests indicated that the differences between means is normally distributed (see Table 11). Visual inspection of the distributional characteristics of the data using Q-Q plots qualitatively corroborated the quantitative results (see Appendix B8 for plots and additional indices). We then proceeded to test the relevant hypotheses with two paired samples *t*-test (bidirectional). Associated descriptive statistics are depicted in Table 12.

Table 11

Shapiro-Wilk's W test of Gaussianity.

			W	p
V_{00}	-	V_{01}	0.990	0.855
V_{10}	-	V_{11}	0.995	0.995

Note. Significant results suggest a deviation from normality.

[136] The associated CRAN URL of the R package is as follows: https://cran.r-project.org/web/packages/moments/

[137] The corresponding formula for the Fisher-Pearson coefficient of skewness is as follows (see also Doane & Seward, 2011).:
$\frac{\sum_{i=1}^{N} (Y_i-\bar{Y})^3/N}{s^3}$, where $\bar{Y}$ signifies the mean, *s* the standard deviation, and *N* the number of data points

[138] The definition of Pearson's measure of kurtosis is:
$\frac{\sum_{i=1}^{N} (Y_i-\bar{Y})^4/N}{s^4}$, where $\bar{Y}$ signifies the mean, *s* the standard deviation, and *N* the number of data points.

Table 12

Descriptive statistics for experimental conditions.

	N	Mean	SD	SE
V_{00}	70	3.820	1.020	0.122
V_{01}	70	3.290	1.020	0.122
V_{10}	70	6.630	1.010	0.121
V_{11}	70	7.110	1.010	0.121

Variable declarations:

V_{00}= high luminance stimuli → low luminance stimuli (singular measurement)

V_{01}= high luminance stimuli → low luminance stimuli (binary measurement)

V_{10}= low luminance stimuli → high luminance stimuli (singular measurement)

V_{11}= low luminance stimuli → high luminance stimuli (binary measurement)

Both *t*-test were statistically significant. The first comparison indicated that V_{00} was rated significantly higher relative to V_{01}, M_{Δ}=-0.53; $t(69)$=-2.96, p=0.004, 95%*CI* [0.17, 0.89]; Cohen's d=0.35, 95%*CI* for d [0.11, 0.59]. On the other hand, V_{10} was rated significantly lower as compared to V_{11} M_{Δ}=-0.48; $t(69)$=-2.96, p=0.005, 95%*CI* [-0.81, -0.15]; Cohen's d=-0.34, 95%*CI* for d [-0.58, 0.10]. A comprehensive tabular summary is provided in Table 13 and the data is visualised in Figure 42 and Figure 43.[139] Taken

[139] In addition, a complete summary of the results and an interactive visualisation of the associated Vovk-Sellke maximum *p*-ratio (Sellke et al., 2001; Vovk, 1993) is provided under the following URL as a HTML-file: http://irrational-decisions.com/phd-thesis/exp2/frequentist-analysis-exp2.html

together, the results corroborate our *a priori* hypotheses and provide a conceptual cross-validation of the findings reported by (White et al., 2015, 2014b).

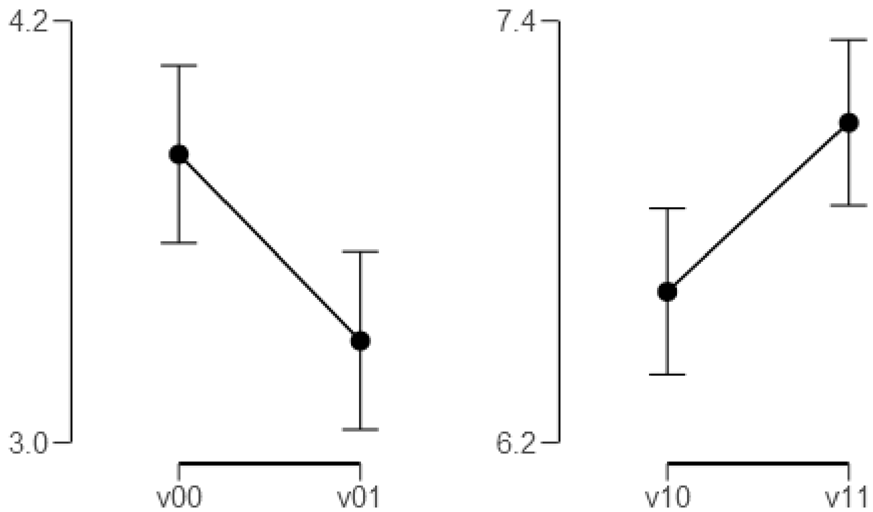


Figure 42. Visual summary of differences between means with associated 95% confidence intervals.

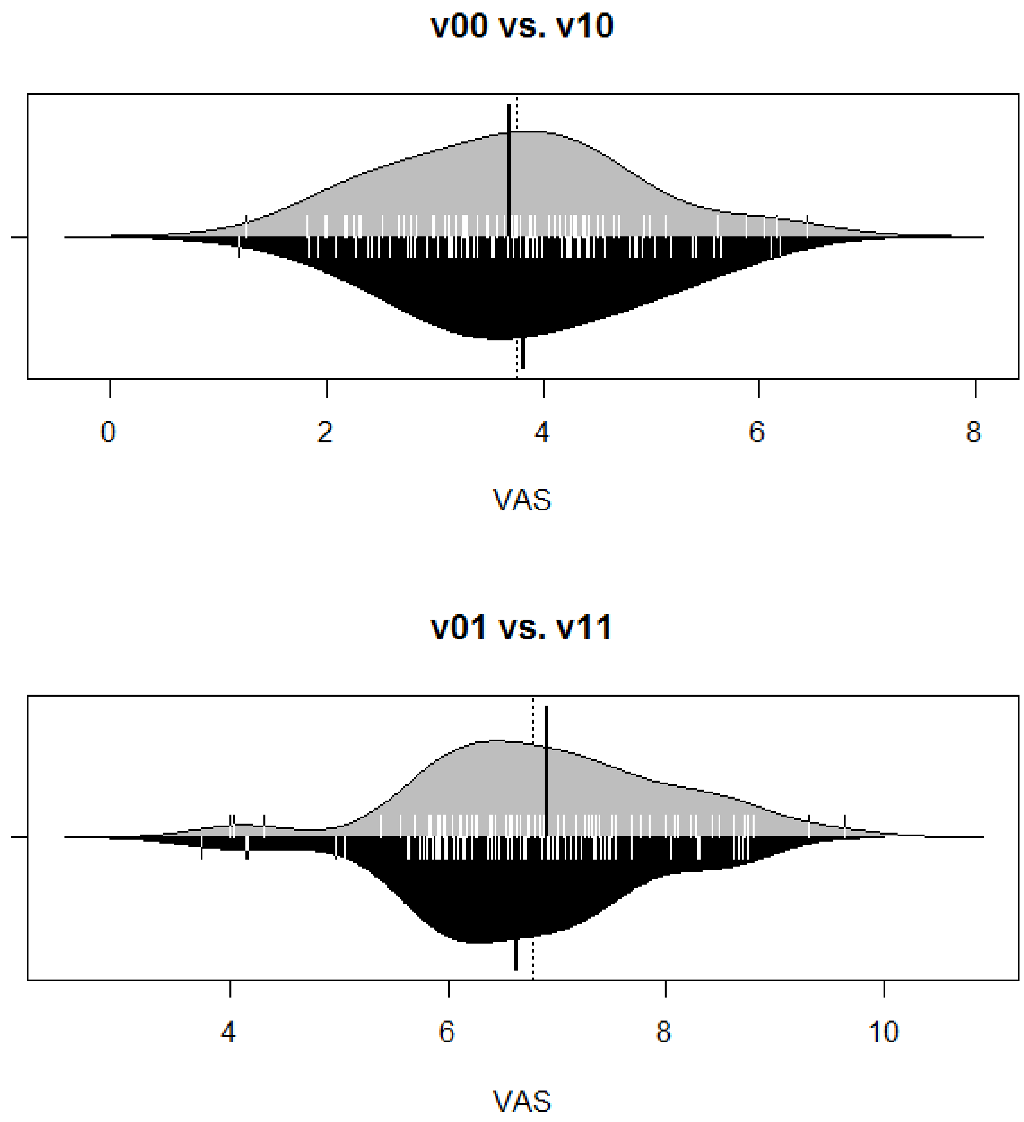


Figure 43. Asymmetric beanplots (Kampstra, 2008) depicting the differences in means and various distributional characteristics of the dataset.

Note: The thin horizontal lines represent individual data points and the thick black line indicates the grand mean per condition. The shape of the bean visualises the density of the distributions (Gaussian kernel). It can be seen the beanplots provide much more detailed information about the data as compared to classical boxplots (but see Juutilainen et al., 2015).

Table 13

Paired samples t-tests and nonparametric Wilcoxon signed-rank tests.

								95% CI for Location Parameter			95% CI for Effect Size	
	Test	**Statistic**	**df**	**p**	**VS-MPR***	**Location Parameter**	**SE Difference**	**Lower**	**Upper**	**Effect Size**	**Lower**	**Upper**
v00 - v01	Student	2.960	69	0.004	15.944	0.530	0.179	0.173	0.887	0.354	0.111	0.594
	Wilcoxon	1687.000		0.009	8.409	0.520		0.126	0.872	0.358	0.104	0.568
v10 - v11	Student	-2.871	69	0.005	12.977	-0.480	0.167	-0.814	-0.146	-0.343	-0.583	-0.101
	Wilcoxon	766.000		0.005	13.162	-0.481		-0.834	-0.151	-0.384	-0.587	-0.134

* Vovk-Sellke Maximum p -Ratio: Based on the p -value, the maximum possible odds in favor of H_1 over H_0 equals 1/(-e p log(p)) for $p \leq .37$ (Sellke, Bayarri, & Berger, 2001).

Note. For the Student t-test, location parameter is given by mean difference d ; for the Wilcoxon test, effect size is given by the Hodges-Lehmann estimate.

Note. For the Student t-test, effect size is given by Cohen's d ; for the Wilcoxon test, effect size is given by the matched rank biserial correlation.

3.4.2 Bayes Factor analysis

The parametrisation of the model was identical to Experiment 1. We applied the same noncommittal Cauchy priors in line with the "objective Bayes" (Berger, 2006) philosophy discussed earlier.

H_1: $\delta \sim \text{Cauchy}(0,r)$

The first contrast (experimental condition V_{00} vs. V_{01}) resulted in a Bayes Factor of $BF_{10} \approx 7.02$ indicating that the data are about 7 times more likely under H_1 than under H_0, i.e., $P(D \mid H_1) \approx 7.02$. Consequently, the reciprocal indicated that $P(D \mid H_0) \approx 0.14$. The second comparison (V_{10} vs. V_{11}) produced a Bayes Factor of $BF_{10} \approx 5.62$, i.e., $P(D \mid H_1) \approx 5.62$; and conversely $P(D \mid H_0) \approx 0.18$. The associated errors were extremely small for both BFs as can be seen in Table 14. According to Jeffreys' heuristic interpretational schema, both Bayes Factors provide "moderate evidence for H_1". Descriptive statistics and the associated 95% Bayesian credible intervals are given in Table 15. In addition, the results are visualised in Figure 44. A complete summary of the results of the Bayes Factor analysis is available under the following URL:

http://irrational-decisions.com/phd-thesis/bayesfactor-analysis-exp2.html

In addition, we made the underlying JASP analysis script available for download to facilitate analytical reviews as suggested by Sakaluk, Williams, & Biernat (2014):

http://irrational-decisions.com/phd-thesis/analysis-script-exp2.jasp

Table 14

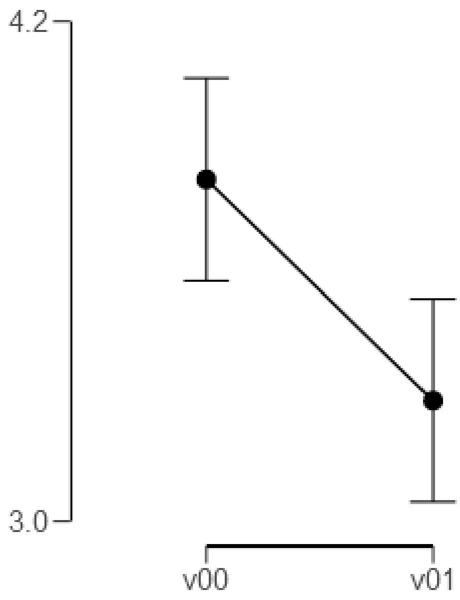
Bayes Factors for the orthogonal contrasts.

		BF_{10}	error %
v00	- v01	7.019	1.296e -6
v10	- v11	5.615	1.603e -6

Table 15

Descriptive statistics with associated 95% Bayesian credible intervals.

					95% Credible Interval	
	N	Mean	SD	SE	Lower	Upper
v00	70	3.820	1.020	0.122	3.577	4.063
v01	70	3.290	1.020	0.122	3.047	3.533
v10	70	6.630	1.010	0.121	6.389	6.871
v11	70	7.110	1.010	0.121	6.869	7.351



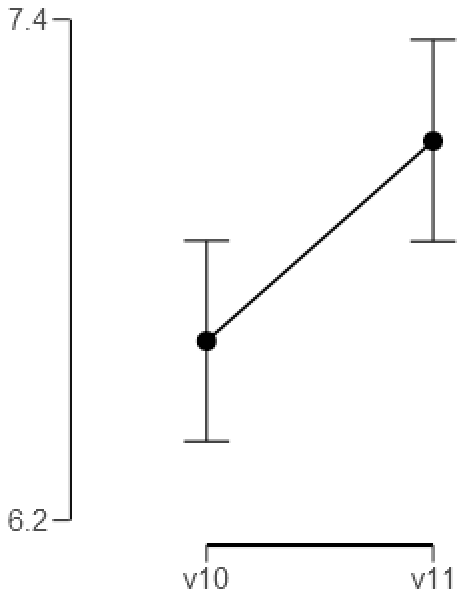


Figure 44. Means per condition with associated 95% Bayesian credible intervals.

Figure 45 and Figure 46 provide a visual synopsis the most essential results of the Bayesian analysis in a concise format: 1) a visualisation the prior distribution of the effect sizes, 2) the associated posterior distributions, 3) the associated 95% Bayesian credible intervals, 4) the posterior medians, 5) the Bayes Factors, 6) the associated

Savage–Dickey density ratios[140] (E. J. Wagenmakers et al., 2010), 7) pie-charts of the Bayes Factor in favour of H_1.

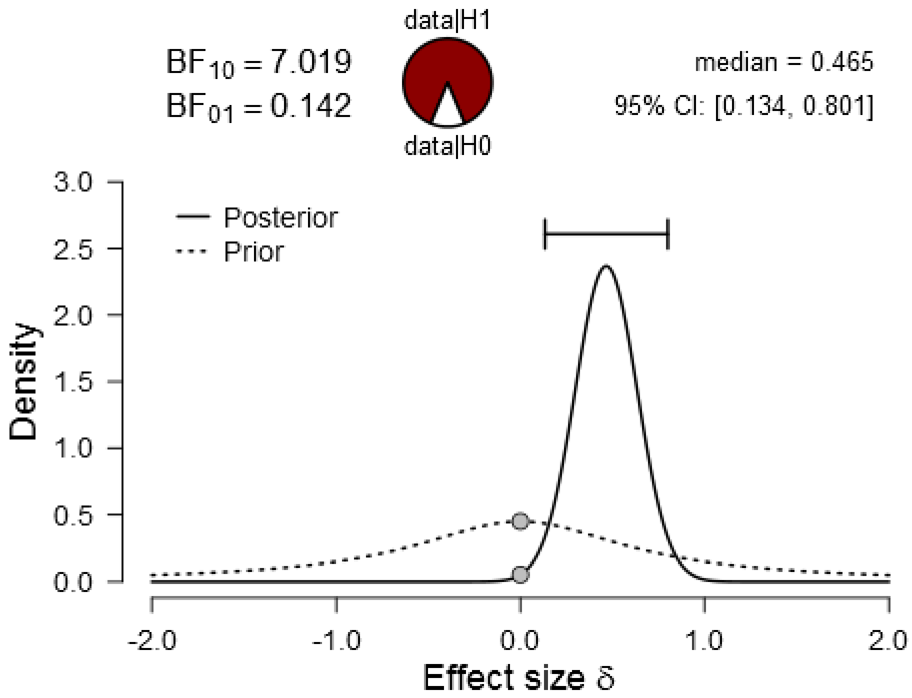


Figure 45. Prior and posterior plot for the difference between V_{00} vs. V_{01}.

[140] For an interactive visualisation see http://irrational-decisions.com/?page_id=2328

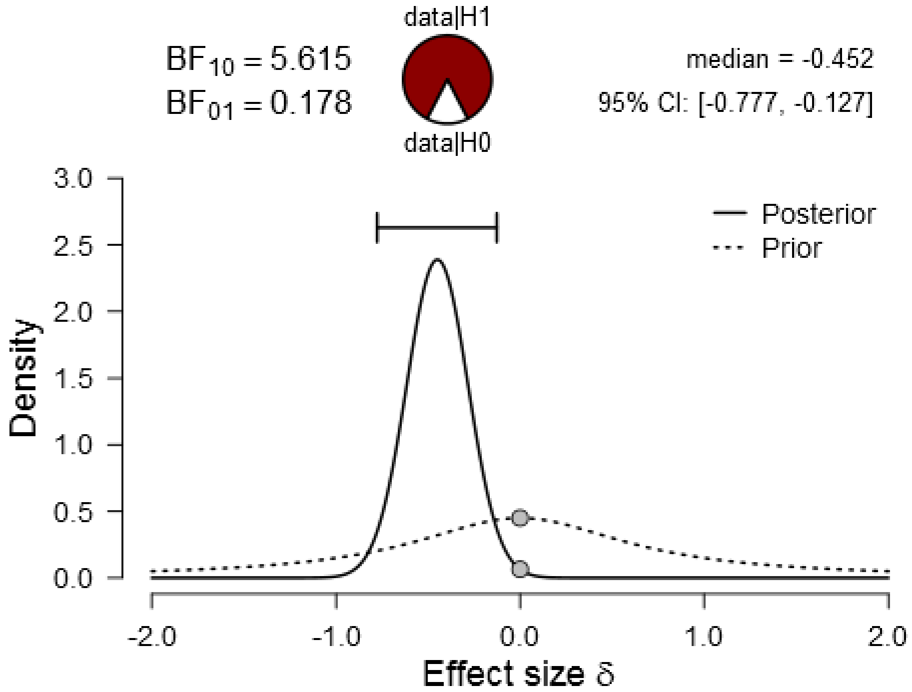


Figure 46. Prior and posterior plot for the difference between V_{10} vs. V_{11}.

In order to establish the robustness of our findings (i.e., their independence from specific priors), we performed Bayes Factor robustness checks for various Cauchy priors per comparison. The results indicated that the outcome was reasonably stable under various parametrisations of the Cauchy priors. For the first comparison (V_{00} vs. V_{01}) the maximum Bayes Factor was obtained at $r \approx 0.29$ (max $BF_{10} \approx 9.37$). For the second comparison (V_{10} vs. V_{11}) the maximum evidence in favour of H_1 was associated with $r \approx 0.27$ (max $BF_{10} \approx 7.68$). Details of the BF robustness analysis are provided in Figure 47 and Figure 48, respectively.

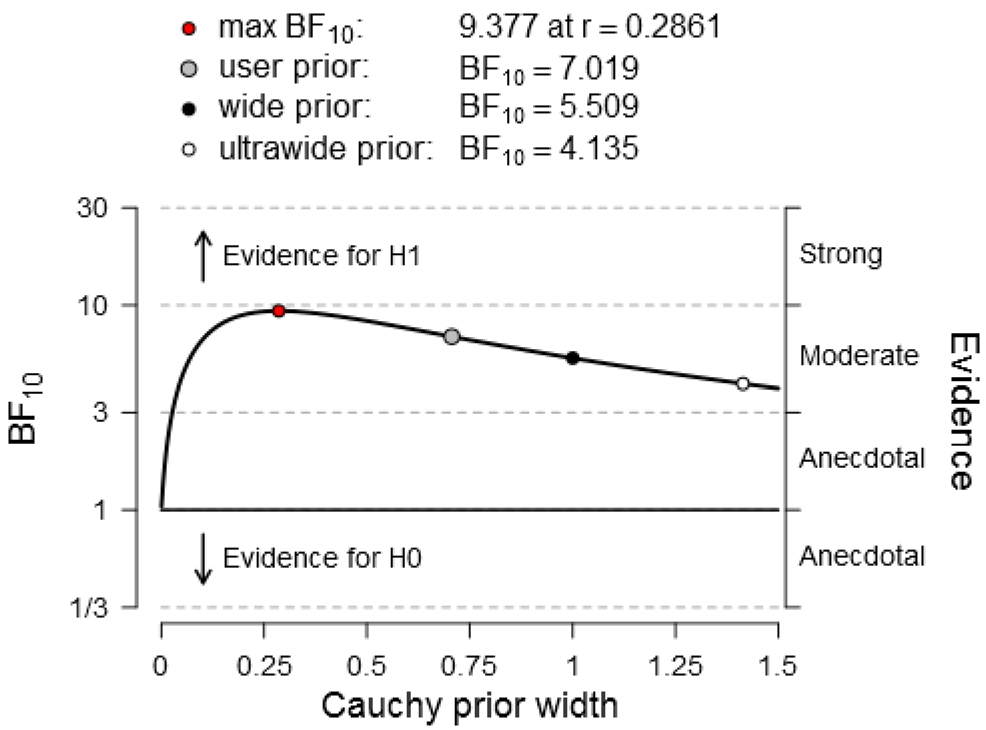


Figure 47. Bayes Factor robustness check for condition V_{00} vs. V_{10} using various Cauchy priors.

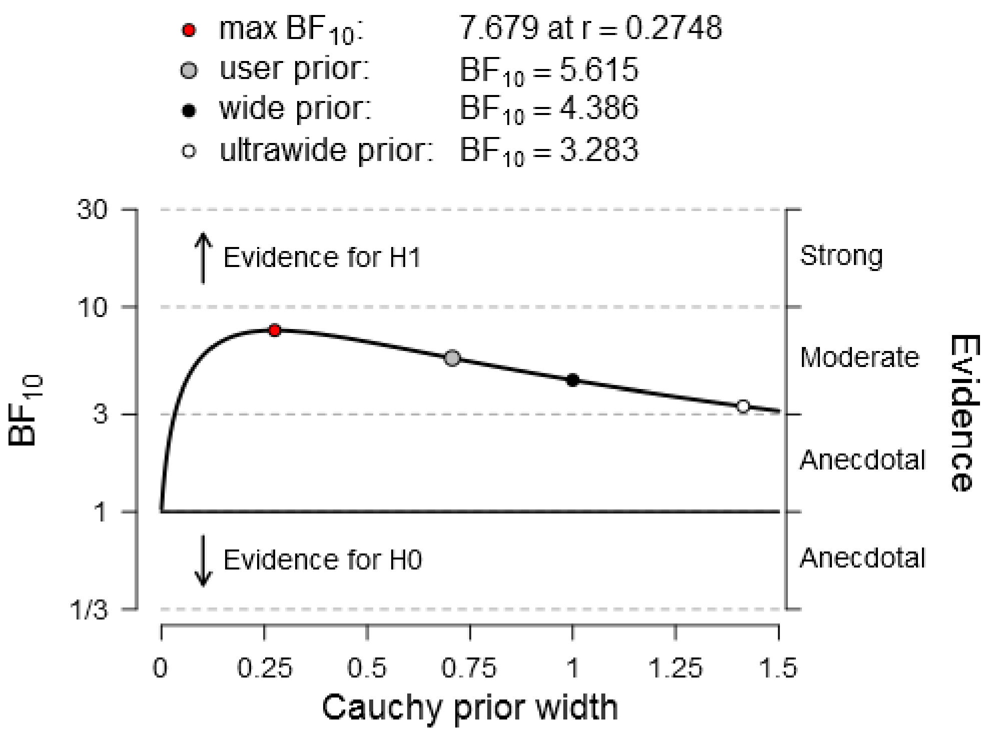


Figure 48. Bayes Factor robustness check for condition V_{01} vs. V_{11} using various Cauchy priors.

Similar to the analysis reported in Experiment 1, we performed a sequential Bayes Factor analysis to examine the accumulation of evidence in favour of H_1 as a function of the number of data points/participants. The results of this analysis are visualised in Figure 49 and Figure 50.

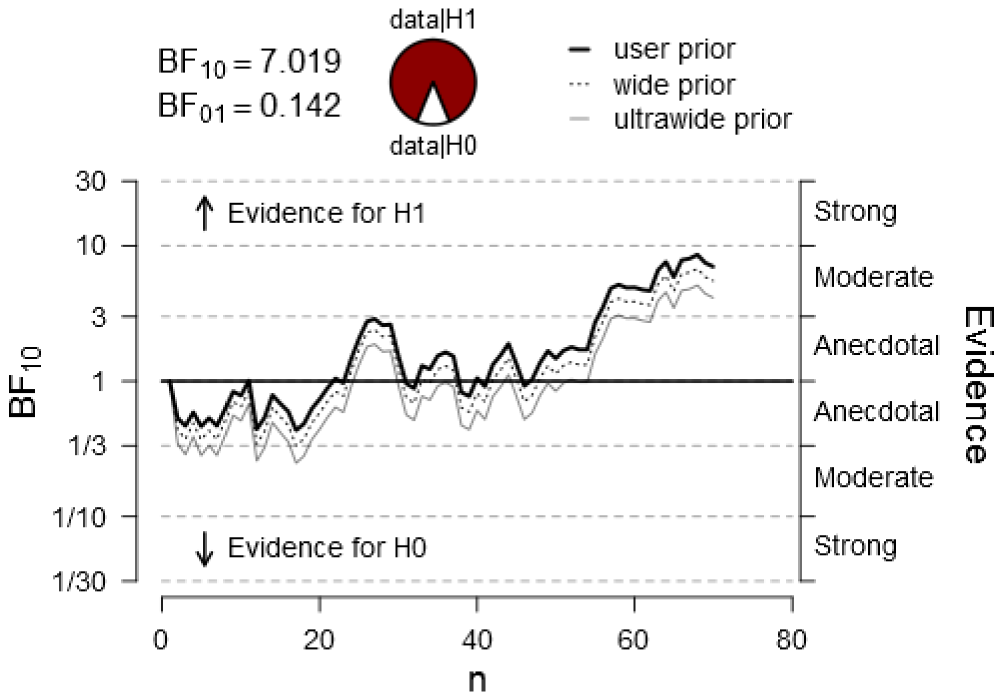


Figure 49. Sequential analysis depicting the accumulation of evidence as *n* accumulates over time (for experimental condition V_{00} vs. V_{10}).

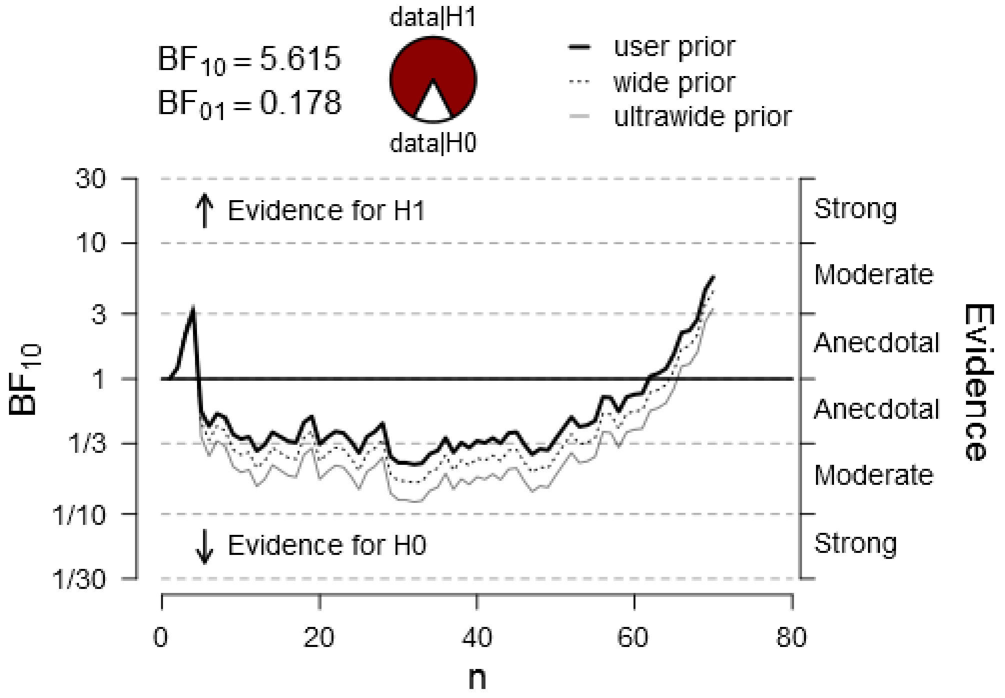


Figure 50. Sequential analysis depicting the accumulation of evidence as n accumulates over time (for experimental condition V_{00} vs. V_{10}).

In sum, the Bayes Factor analysis corroborated our initial hypotheses and provided an analytic cross-validation of the preceding frequentist analysis. We demonstrated the robustness of our finding under various priors and we investigated the accrual of evidence as a function of time (viz., as a function of the number of participants). The Bayes Factor provided a quantitative metric for the “strength of evidence” which was unavailable in the frequentist framework. In addition, the results of the analysis can be utilised for future research in the sense of Dennis Lindley’s motto: “Today's posterior is tomorrow's prior” (Lindley, 1972), or as Richard Feynman put it “Yesterday's sensation is today's calibration” to which Valentine Telegdi added“...and tomorrow's background”. In the long run, this incremental (subjective) Bayesian philosophy of science thus facilitates the cumulative (quasi-evolutionary) progress of science because it enables the explicit integration of prior knowledge. This is a huge advantage over NHST. The importance of this generic argument cannot be overstated.

3.4.3 Bayesian parameter estimation using Markov chain Monte Carlo methods

This section reports the application Bayesian parameter estimation via Markov chain Monte Carlo (MCMC) methods. We utilised the same hierarchical Bayesian model as described in Experiment 1. That is, we specified the same priors on all parameters and performed the simulation with the same specifications. As in the previous analysis, we performed the MCMC simulation with 100000 iterations, 500 adaptation steps, and 1000 burn-in steps (no thinning, 3 Markov chains in parallel). We will first report the convergence diagnostics and we will then proceed to examine the posterior distributions.

3.4.3.1 MCMC simulation output analysis and convergence diagnostics

The converge diagnostics indicated that the Markov Chain reached the steady-state (equilibrium) distribution π. $\hat{R}$ (the potential scale reduction factor) had a value of 1, indicating that the chain reached its equilibrium distribution and the ESS (effective sample size) had an acceptable value (i.e., smaller than 100000). On this basis we proceeded with the analysis and examined the posterior distribution. Exact diagnostic metrics are provided in Table 16. Detailed visual and numerical diagnostics are attached in Appendix C4.

Table 16

MCMC convergence diagnostics based on 100002 simulations for the difference in means between experimental condition V_{00} vs. V_{10}.

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334



             mean     sd mcmc_se n_eff Rhat
mu_diff     0.524  0.183   0.001 62608    1
sigma_diff  1.467  0.143   0.001 46091    1
nu         37.878 30.016   0.209 20702    1
eff_size    0.360  0.129   0.001 63638    1
diff_pred   0.527  1.573   0.005 99385    1
```

Model parameters:

- μ_Δ (mu_diff): The mean pairwise difference between experimental conditions
- σ_Δ (sigma_diff): the scale of the pairwise difference (a consistent estimate of SD when nu is large)
- ν (nu): The degrees-of-freedom for the bivariate *t* distribution fitted to the pairwise difference
- δ (eff_size): the effect size calculated as $(\mu_\Delta - 0)/\sigma_\Delta$.
- $\mu_{\Delta pred}$ (diff_pred): predicted distribution for a new datapoint generated as the pairwise difference between experimental conditions

Convergence diagnostics:

- mcmc_se (Monte Carlo Standard Error, MCSE): The estimated standard error of the MCMC approximation of the mean.
- n_eff (Effective Sample Size, ESS): A crude measure of effective MCMC sample size.
- Rhat (Shrink factor, $\hat{R}$): the potential scale reduction factor (at convergence, $\hat{R} \approx 1$).

3.4.3.2 Bayesian parameter estimation for the difference between experimental condition V_{00} vs. V_{10}

The posterior predictive plot indicated a good model fit (illustrated in Figure 51). The estimated mean difference between experimental condition V_{00} vs. V_{10} was $\mu_\Delta \approx 0.52$ with a 95% HDI ranging from [-0.17, -0.89]. The associated effect size was estimated to be $\delta \approx 0.36$ and the associated 95% HDI spanned [0.11 -0.61]. The standard deviation of the difference was estimated to be $\sigma_\Delta \approx 1.47$. We utilised the 95% HDI in combination with a predefined ROPE in order draw inferences concerning our *a priori* hypothesis. The ROPE for the means difference and the effect size did not overlap with 95% HDI. Based on the previously discussed ROPE/HDI decision algorithm (Kruschke, 2014), we concluded that H_0 can be rejected and H_1 accepted. A numerical summary of the results[141] is given in Table 17 and a comprehensive visual synopsis is provided in Figure 51. In sum, the analysis reconfirmed our previous statistical inference and lends further support to our conclusions. Moreover, we obtain precise parameter estimates

[141] Note: The reported posterior parameter estimates might vary slightly because they are based on a different MCMC chains and therefore influenced by the randomness in the MCMC chains. We ran the same analyses several times to establish the robustness of the parameter estimates across MCMC samples.

with associated high-density intervals which were unavailable in the previous analyses.[142]

Table 17

MCMC results for Bayesian parameter estimation analysis based on 100002 simulations for the difference in means between experimental condition V_{00} vs. V_{10}.

	mean	sd	HDIlo	HDIup	%<comp	%>comp
mu_diff	0.523	0.183	0.169	0.886	0.002	0.998
sigma_diff	1.467	0.143	1.199	1.762	0.000	1.000
nu	37.892	30.417	2.661	98.663	0.000	1.000
eff_size	0.360	0.129	0.110	0.613	0.002	0.998
diff_pred	0.533	1.571	-2.664	3.563	0.359	0.641

Note. 'HDIlo' and 'HDIup' are the limits of a 95% HDI credible interval. '%<comp' and '%>comp' are the probabilities of the respective parameter being smaller or larger than 0.

[142] Based on the richness of information supplied by the MCMC based Bayesian parameter estimation approach, we argue that this statistical inferential technique is by a large margin superior to NHST and Bayes Factor analysis (Kruschke & Liddell, 2015, 2017a; Kruschke & Vanpaemel, 2015).

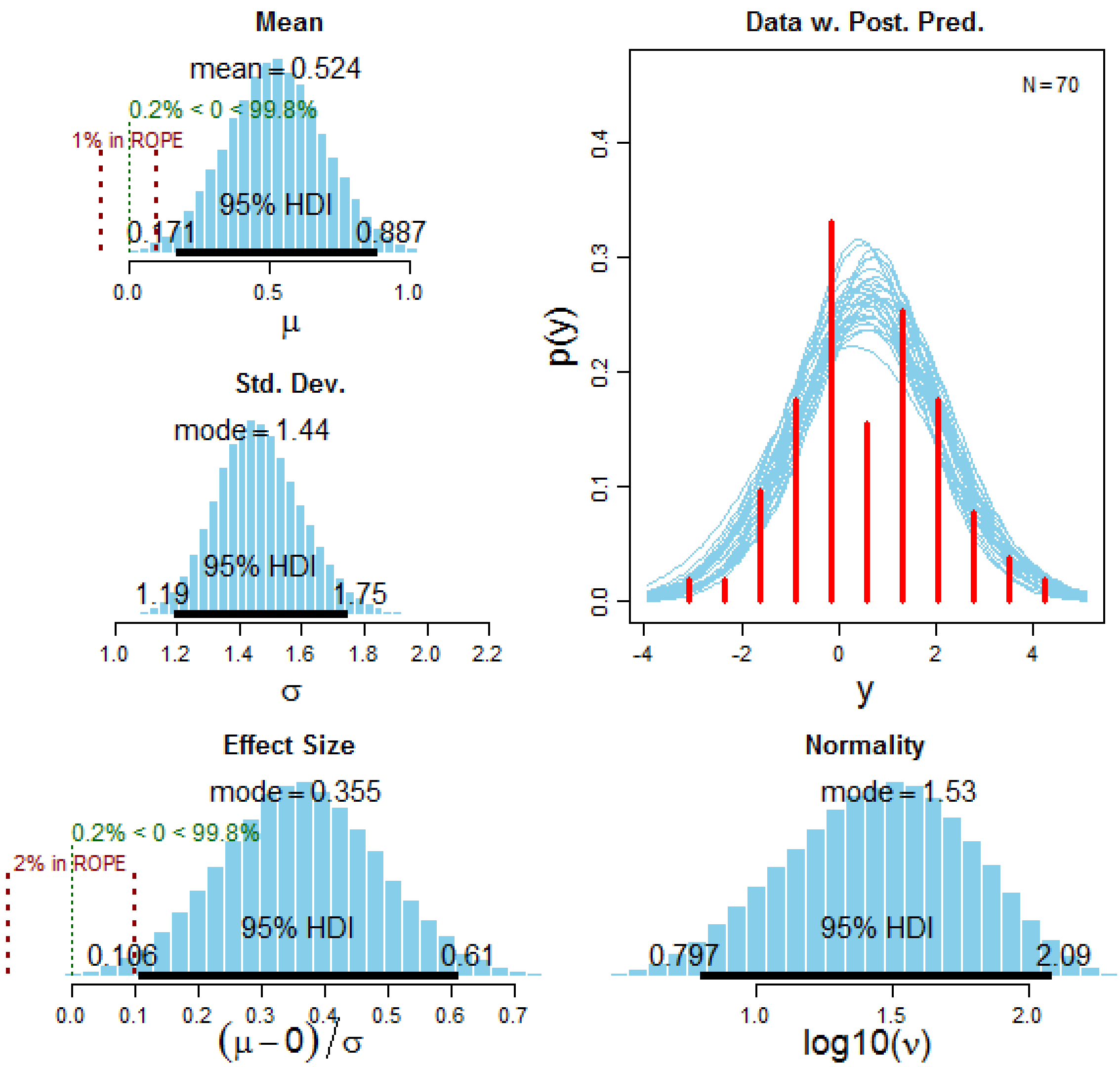


Figure 51. Comprehensive summary of the Bayesian parameter estimation.

Left panel: Posterior distribution of the difference between means (experimental condition V_{00} vs. V_{10}) with associated 95% high density credible intervals and ROPE [-0.1,0.1], the standard deviation of the estimated difference and the corresponding effect size δ with its associated ROPE ranging from [-0.1,0.1] and 95% HDI.

Right panel: Posterior predictive plot (n=30) for the mean difference. The normality parameter $\log_{10}(v)$ with accompanying 95% HDI.

3.4.3.3 Bayesian parameter estimation for the difference between experimental condition V_{01} vs. V_{11}

The convergence diagnostics (Table 18, see Appendix C5 for additional details) indicated that the MCMC samples converged to the equilibrium distribution and we proceeded with the inspection of the posterior distributions.

Table 18

MCMC convergence diagnostics based on 100002 simulations for the difference in means between experimental condition V_{00} vs. V_{10}.

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

              mean     sd mcmc_se n_eff Rhat
mu_diff     -0.485  0.170   0.001 60960    1
sigma_diff   1.358  0.136   0.001 41291    1
nu          35.160 28.789   0.208 19274    1
eff_size    -0.361  0.130   0.001 57623    1
diff_pred   -0.488  1.454   0.005 98609    1
```

As can be seen in Figure 52, the posterior predictive plot indicated a good approximation of the empirical data. The estimated mean difference between experimental condition V_{01} vs. V_{11} was $\mu_{\Delta} \approx -0.48$, 95% HDI [-0.82, -0.15]. The effect size was $\delta \approx -0.36$ and the associated 95% HDI ranged from [-0.62 -0.10]. The standard deviation of the difference was $\sigma_{\Delta} \approx 1.36$, 95% HDI [1.10, 1.63]. The difference between means was credible and the ROPE [-0.1, 0.1] for the difference in means and the corresponding effect size did not overlap with 95% HDI. We thus rejected H_0 and accepted H_1. A quantitative overview of the results is given in Table 19 and Figure 52 provides a comprehensive visual summary. Taken together, the analysis corroborated our previous analyses and strengthened the credibility of our *a priori* hypotheses from a Bayesian point of view.

Table 19

MCMC results for Bayesian parameter estimation analysis based on 100002 simulations for the difference in means between experimental condition V_{01} vs. V_{11}.

	mean	sd	HDIlo	HDIup	%<comp	%>comp
mu_diff	-0.485	0.171	-0.817	-0.143	0.998	0.002
sigma_diff	1.358	0.137	1.096	1.634	0.000	1.000
nu	35.134	28.790	2.405	93.144	0.000	1.000
eff_size	-0.361	0.131	-0.618	-0.103	0.998	0.002
diff_pred	-0.485	1.461	-3.373	2.404	0.635	0.365

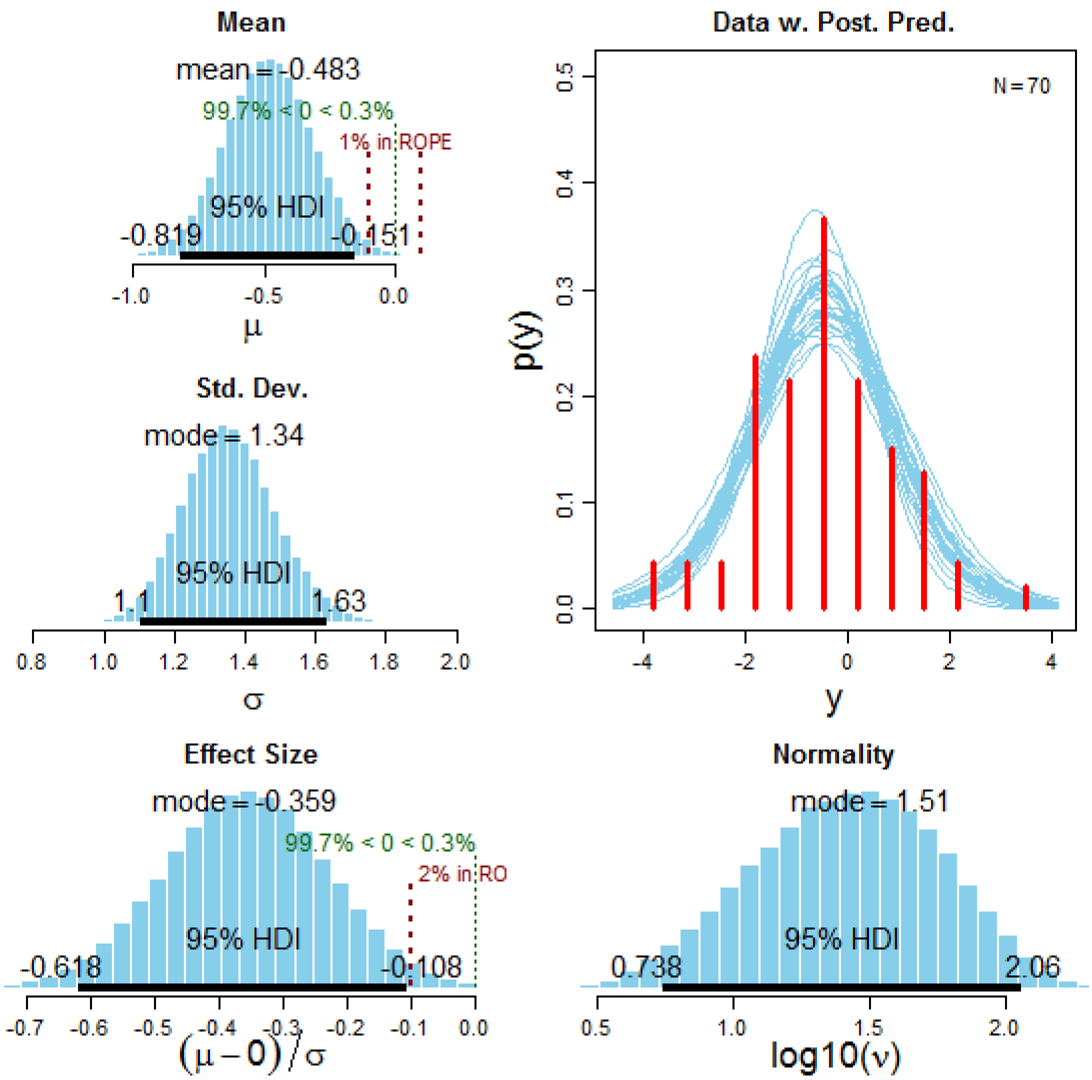


Figure 52. Visual synopsis of the results of the Bayesian parameter estimation.

Left panel: Posterior distribution of the difference between means (experimental condition V_{01}vs. V_{11}) with associated 95% high density credible intervals, and ROPE [-0.1,0.1],the standard deviation, of the estimated difference and the corresponding effect size. Right panel: Posterior predictive plot (*n*=30) for the mean difference. The normality parameter $\log_{10}(\nu)$ with accompanying 95% HDI.

In sum, we concluded that the differences of means between experimental conditions V_{00} vs. V_{01} and V_{10} vs. V_{11} are credible. That is, both pairwise comparisons resulted in values that were credibly different from zero. Hence, we rejected H_0 for both hypotheses. The conclusion is motivated by the nonoverlapping position of the 95% equal-tail high density credible interval relative to the region of practical equivalence. This inference is congruent with the conclusion based on the previous frequentists NHST analysis and the Bayes Factor analysis. In addition, we performed a correlation analysis by computing a classical Pearson's product-moment correlation coefficient and a Bayesian MCMC based alternative. The results of this supplementary analysis are attached in Appendix C7.

3.5 Discussion

In conclusion, our results indicate that psychophysical measurements play a constructive role in perceptual processes. Moreover, our findings are in line with those reported in the domain of attitudinal judgments (White et al., 2015, 2014b). Our investigation can be regarded as a psychophysical analogon of the measurement problem in quantum physics (discussed in more detail in a subsequent chapter). In quantum physics, it is a well-replicated finding that the mere act taking a measurement changes the process under investigation. That is, the evolution of the system under investigation, be it physical or cognitive, is conditional on observation (e.g., einselection/wave-function collapse). The constructive role of measurements is incongruent with classical (deterministic) Markov models which assume that the system under investigation is always in a fixed and discrete ontological state (even though the exact state might be unknown, e.g., as postulated various hidden-variable accounts).

An important question concerns the exact definition (operationalisation) of what constitutes a psychophysical measurement. It is entirely possible that participants make covert judgments in trails where no response is rquired. We cannot rule out this possibility due to the methodological impossibility to directly access introspective cognitive states. Such implicit judgment might take place below the threshold of conscious awareness and participants themselves might therefore be unable to report on such automatic processes. Only neuroimaging studies would be able to resolve this question. Using an appropriate experimental design on could subbstract the neuronal activity associated with conditions in which one expects unconscious judgments from a baseline level of activity in order to gain insight into this aspect of information processing. In addition, one could use electromyography in order measure minute movements at the muscular level (e.g., at the muscle tissue of the hand or fingers). Moreover, it is likely that EEG measurments could pick up preparatory action potentials at the level of the premotor cortex long before an actual motor response is emitted. In an ideal case one would combine EEG and fMRI techniques in order to tobtain a more complete picture (EEG has a temporal resolution and a low spatial resolution; the opposite holds true for fMRI). By coupling the signals obtained from the two modalities one could then draw joint inferences about the underlying cognitive (unconscious) mechanisms. (In addition, acquiring simultaneous EEG and functional MRI would have several methodological advantges as potential confounds would be balanced out, thereby increasing the reliability and validity of the measurements.)

However, even if partcipants engaged in such unconscious judgments there would be a difference between explicit and implicit modes of responding.

Another question worth discussing concern the question of the level at which constructive inference takes place. It could be cogently argued that measurment effects could in principle be prent across the whole experiment. This is an interesting line of though and it relevant from a complex systems perspective in which one assumes that principles at the micro scale of the system (e.g., an individual experimental trial) are scale-invariant and are conseuqntly reflected at the macro level of the system (e.g., the entire experiment). We are in no position to answer this question conclusively (due to a lack of relevant data). However, this line of thought might even turn out to be relevant for the acute replication crisis science is currently facing. If a scientific experiment as a whole constitutes a measurment one could argue that the order in which experiments are conducted matters (due to constructive interference). This is a sensible idea which deserves further investigation. Currently, science assumes that replication is independent of the order in which experiments are conducted. However, this assumption might not stand the empirical test.

More generally the important questionof what exactly constitutes a measurment is analogous to adamantine "measurement problem" in quantum physics which is matter of intense debate in the physics community. We will address this operationalsiational problem in more detail in the general discussion (§ 6.3.2). At this point it is sufficient to note that an exact definition is currently unavailable and that there is no consensus in the scientific community.

CHAPTER 4. EXPERIMENT #3: NONCOMMUTATIVITY IN SEQUENTIAL AUDITORY PERCEPTUAL JUDGMENTS

4.1 Experimental purpose

Based on the results of our previous experiments, we were interested whether the observed effects would be generalisable to another percepetual information processing modality. Therefore, we designed an audiometric psychophysics experiment which was structurally isomorphic to Experiment 1. Thus, Experiment 3 can be regarded as an effort to cross-validate and generalise our previously obtained empirical results. Furthermore, Experiment 3 is a conceptual replication in an effort to establish the robustness of the previous results. Instead of focusing on the perception of luminance as we did in the previously reported experiments, we focused on the subjective perception of loudness (its objectively quantifiable physical equivalent being sound intensity). Much of the impetus for the current psychoacoustics experiment was derived from the pertinent quantum cognition literature which suggests that noncommutativity effects in psychological observables are ubiquitous in many domains of human (and possibly animal[143]) cognition (Atmanspacher, 2014a, 2016; Atmanspacher & Römer, 2012; Z. Wang et al., 2013). Our line of reasoning was as follows: If the same effects as observed in the visual domain in Experiment 1 can be replicated in a different modality of information processing, then we can be more confident that the noncommutativity principle is a general and fundamental property of human perception and cognition. This argument is based on an analogy to computational processes at the neuronal level. Neurons utilise the same neuronal representations and computational principles across modalities, that is, there is no difference between the electrochemical computation principles employed for visual and auditory perception (and all other sensory modalities). That is, the neural code is identical across information processing modalities and across species (Bialek, Rieke, de Ruyter van Steveninck, & Warland,

[143] An investigation of noncommutativity effects in animal perception would provide another powerful cross-validation for the general framework of quantum-like noncommutativity effects in cognitive processes. However, we a not aware that such research has been conducted yet. We would be very interested in studies examining perceptual noncommutativity in non-human primates. The next step further down in the phylogenetics hierarchy would be to investigate those processes, for instance, in bacteria e.g., noncommutativity effects in phototaxis, chemotaxis, and magnetotaxis (Frankel & Bazylinski, 1994; Gest, 1995; Vladimirov & Sourjik, 2009). If perceptual noncommutativity could be demonstrated across different taxa (in addition to different sensory modalities) this provide very strong converging evidence for the generalisability of this principle, viz., scientific consilience (E. O. Wilson, 1998a, 1998b) via methodological polyangulation at multiple levels of biology.

1991; Stanley, 2013). It is thus reasonable to argue that perceptual mechanism follow similar generalisable principles which are modality-unspecific. The current experiment was thus designed to investigate the modality-nonspecificity of noncommutativity effects in a controlled experimental fashion which is directly comparable (i.e., empirical commensurable) to Experiment 1.

4.2 A priori hypotheses

Our *a priori* hypotheses were isomorphic to those formulated in Experiment 1. We focused specifically on noncommutativity effects in auditory perceptual judgments.

H_1: Measuring the intensity of a high loudness stimuli first results in a decrease in the subsequent judgment for low stimuli as compared to the reverse order.

H_2: Measuring the perceived loudness of the low loudness stimuli first results in an increase in the subsequent judgment relative to reverse order.

In symbolic form expressed as follows:

$H_1: AB \neq BA$

where

A = high intensity auditory stimuli

B = low intensity auditory stimuli

4.3 Method

4.3.1 Participants and Design

The experiment was carried out in the psychology laboratory of the University of Plymouth and ethical approval was obtained from the universities human research ethics committee. We recruited participants from the general public using web-based advertising using the Sona participant management software (Sona Experiment Management System®, Ltd., Tallinn, Estonia; http://www.sona-systems.com) which is hosted on the universities webserver. In total, 80 participants participated in the experiment (45 women and 35 men, ages ranging between 18 and 62 years, M_{age} = 26.73; SD_{age} = 7.17).

4.3.2 Apparatus and materials

As in the previous experiments, we utilised the Python (Python Software Foundation, 2013) based software PsychoPy (J. W. Peirce, 2007, 2008) for the creation of the experiment. Auditory stimuli were specified by using the "sound component"[144] in PsychoPy which is based on the "`Pyo`" audio library (a Python module written in C to assist digital signal processing script creation)[145]. We created two auditory stimuli (pure tones, 400Hz) with varying intensity levels, i.e., we fixed the "loudness" parameter in PsychoPy to "0.6" and "0.8", respectively. Recordings of the auditory stimuli can be downloaded from the following URLs in the "waveform audio file" (*.wav) format:

[144] Details can be found under the following URL: http://www.psychopy.org/builder/components/sound.html
[145] http://ajaxsoundstudio.com/pyodoc/

http://irrational-decisions.com/phd-thesis/auditory-stimuli/stimulus-0.6.wav

http://irrational-decisions.com/phd-thesis/auditory-stimuli/stimulus-0.8.wav

The complete source code of the experiment can be downloaded from the following URL as a compressed ZIP archive: http://irrational-decisions.com/?page_id=618

4.3.3 Experimental Design

The structure of the experiment was a repeated measures design consisting of auditory stimuli with different intensity levels. The presentation of stimuli was randomly alternated in order to investigate sequential noncommutativity effects in auditory perceptual. As in Experiment 1, we utilised a fully counterbalanced Latin-square design and the experimental conditions were thus as follows.

Variable declarations for experimental conditions:

V_{00} = low intensity → low intensity

V_{01} = low intensity → high intensity

V_{11} = high intensity → high intensity

V_{10} = high intensity → low intensity

4.3.3.1 Procedure

Before the commencement of the study, participants were briefed and accorded written informed consent. Subsequently, participants were seated in front of a PC equipped with headphones and received further instructions.

4.3.4 Sequential auditory perception paradigm

The entire experimental paradigm was isomorphic with respect to Experiment 1 in order to ensure commensurability between experimental results. The only difference was that we switched the perceptual modality from visual perception to auditory perception in order investigate the generalisability/modality-nonspecificity of our prior experimental findings.

4.4 Statistical Analysis

We applied the same statistical analyses as detailed in Experiment 1. However, for reasons of brevity, we did not perform nonparametric and Bayesian bootstraps (the results converged in our previous analyses). We first conducted a frequentist analysis using parametric and non-parametric techniques. We then performed a Bayes Factor analysis to get a more accurate probabilistic picture of the credibility of the results. Finally, we utilised much more flexible Bayesian parameter estimation techniques using Markov Chain Monte Carlo methods to obtain precise estimates of the relevant parameters. In the later analytical framework, decision concerning our a priori hypotheses were again based on the previously discussed ROPE/HDI algorithm (thereby engaging the engaged reader to construct her own idiosyncratic decision criteria by constructing a ROPEs with varying radii).

Frequentist analysis

We first examined the distributional properties of the dataset. Descriptive statistics are provided in Table 1. The Shapiro-Wilk's *W* test indicated that the data did satisfy the stipulated Gaussianity assumption which is associated with parametric testing procedures (see

Table 21). We also performed the Kolmogorov-Smirnov test, although simulations studies indicate that Shapiro-Wilk test should generally preferred (Razali & Wah, 2011). All formal tests of Gaussianity indicated that parametric testing procedures are appropriate for the data at hand. However, quantitative *p*-value based test of Gaussianity are imperfect and visual inspection via Q-Q plots is generally recommended (see Appendix D for Q-Q plots and additional test results, e.g., the Cramér–von Mises criterion). Visual inspection reconfirmed that the distributional assumptions were satisfied, and we proceeded with parametric testing.

We performed two paired samples *t*-test (i.e., repeated measures t-test, two-tailed) to evaluate our hypotheses.

Table 20

Descriptive statistic for experimental conditions.

	N	**Mean**	**SD**	**SE**
v00	80	2.528	0.995	0.111
v10	80	3.100	1.060	0.119
v01	80	6.590	1.020	0.114
v11	80	6.030	1.030	0.115

Table 21

Shapiro-Wilk's W test of Gaussianity.

		W	**p**
v00	- v10	0.992	0.881
v01	- v11	0.984	0.409

Note. Significant results suggest a deviation from normality.

4.4.1 Parametric paired samples t-tests

The results of both *t*-test (Gosset, 1908) indicated that the differences between sample means were statistically significant at the conventional arbitrary α-level (R. Fisher, 1956). The *t*-tests indicated that low intensity auditory stimuli were on average rated significantly lower in loudness when anteceded by equivalent stimuli (V_{00}; M=2.53, SD=1.00) as compared to low intensity stimuli which were anteceded by high intensity stimuli (V_{10}; M=3.10, SD=1.06), M_{Δ}=-0.57; $t(79)$=-3.38, p=0.001, 95%*CI* [-0.91, -0.24]; Cohen's d=-0.38,[146] 95%*CI* for d [-0.60, -0.15].

By contrast, the loudness of high intensity auditory stimuli were on average rated significantly higher when they were anteceded by low intensity stimuli (V_{01}, M=6.59, SD=1.02) relative to high intensity stimuli anteceded by equivalent stimuli (V_{11}, M=6.03, SD=1.03), M_{Δ}=0.56; $t(79)$=3.44, p<0.001, 95%*CI* [0.24, 0.88]; Cohen's d=-0.38, 95%*CI* for d [0.16, 0.60]. A visual representation of the results is provided in Figure 53 and a detailed summary is given in Table 23.

[146] Effect sizes were calculated based on the formula described by Moors (2011):
$d = \frac{\bar{x}_1 - \bar{x}_2}{s}$ where the pooled standard deviation (s) is defined as $s = \sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2-2}}$

Furthermore, we computed various alternative statistics (e.g., the Vovk-Sellke Maximum *p*-Ratio, VS-MPR). A numerical summary is provided in Table 3. In addition, a comprehensive summary of the complete results is provided under the following URL:

http://irrational-decisions.com/phd-thesis/exp3/results-exp3.html

The pattern of results was congruent with those obtained in Experiment 1 and confirmed our *a priori* hypotheses. In other terms, the results provided a cross-validation of our previous findings and support the generalisability of our findings across perceptual modalities. We followed-up with a Bayes Factor analysis which is a much more powerful analytic procedure which circumvents the well-documented logical flaws associated with frequentist NHST.

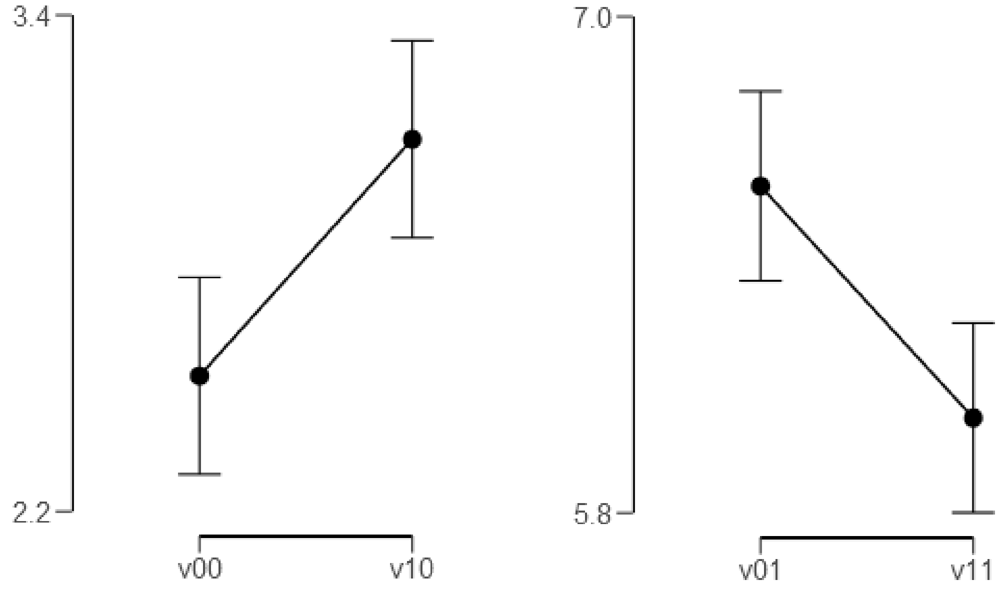


Figure 53. Visualisation of differences in means between conditions with associated 95% confidence intervals.

Table 22

Paired samples t-test and nonparametric Wilcoxon signed-rank tests

	Test	Statistic	df	p	VS-MPR*	Location Parameter	SE Difference	95% CI for Location Parameter		Effect Size	95% CI for Effect Size	
								Lower	**Upper**		**Lower**	**Upper**
v00 - v10	Student	-3.379	79	0.001	47.928	-0.572	0.169	-0.909	-0.235	-0.378	-0.604	-0.150
	Wilcoxon	976.000		0.002	29.280	-0.560		-0.894	-0.218	-0.398	-0.587	-0.167
v01 - v11	Student	3.438	79	9.382e -4	56.247	0.560	0.163	0.236	0.884	0.384	0.156	0.610
	Wilcoxon	2299.000		0.001	47.733	0.626		0.286	0.944	0.419	0.192	0.604

* Vovk-Sellke Maximum *p* -Ratio: Based on the *p* -value, the maximum possible odds in favor of H_1 over H_0 equals 1/(-e *p* log(*p*)) for $p \leq .37$ (Sellke, Bayarri, & Berger, 2001).

Note. For the Student t-test, location parameter is given by mean difference *d* ; for the Wilcoxon test, effect size is given by the Hodges-Lehmann estimate.

Note. For the Student t-test, effect size is given by Cohen's *d* ; for the Wilcoxon test, effect size is given by the matched rank biserial correlation.

4.4.2 Bayes Factor analysis

We used the same specification for the Bayesian model as in the previous experiments. The resulting Bayes Factor for the first pairwise comparison (experimental condition V_{00} vs. V_{10}) was $BF_{10} \approx 21.64$ which can be interpreted as strong evidence for H_1 in Jeffreys' heuristic schema. The data is thus approximately 21 times more likely under H_1 than under H_0, $P(D \mid H_1) \approx 21.64$; and its reciprocal is $P(D \mid H_0) \approx 0.05$. The second contrast resulted in a BF_{10} of ≈ 25.63 which falls in the same category, thereby indicating that $P(D \mid H_1) \approx 25.63$; $P(D \mid H_0) \approx 0.04$. All hypotheses were tested two-tailed. However, it could be argued that directional one-tailed tests would be appropriate, given the previously obtained results. In this case the respective Bayes Factors would be simply multiplied by a factor of two. Therefore, we report results for one-tailed test which renders the statistics directly commensurable between experiments and thence across perceptual modalities. Descriptive statistics and the associated Bayesian 95% Bayesian credible intervals are given in Table 24. In addition, the results are visualised in Figure 54 and prior and posterior plots are provided in Figure 55 and Figure 56, respectively. For reasons of brevity, we will not discuss the analysis in greater detail. Additional information can be found in Appendix D (e.g., Bayes Factor robustness check for various Cauchy priors, Sequential analysis of the accumulation of evidence, etc.).

In sum, the results corroborate our previous analysis and indicate probabilistically that the evidence for H_1 is strong (in Jeffrey's heuristic interpretational scheme discussed before). In direct comparison to Experiment 1, both Bayes Factors indicate that the evidence for noncommutativity is even stronger for auditory perceptual judgments. Recall that the Bayes Factors for Experiment 1 were $BF_{10} \approx 9.20$ and $BF_{10} \approx 24.82$, respectively.

Table 23

Bayes Factors for orthogonal contrasts.

		$\mathbf{BF_{10}}$	**error %**
v00	- v10	21.637	1.616e -7
v01	- v11	25.629	1.460e -7

Table 24

Descriptive statistics and associated Bayesian 95% credible intervals.

					95% Credible Interval	
	N	**Mean**	**SD**	**SE**	**Lower**	**Upper**
v00	80	2.528	0.995	0.111	2.307	2.749
v10	80	3.100	1.060	0.119	2.864	3.336
v01	80	6.590	1.020	0.114	6.363	6.817
v11	80	6.030	1.030	0.115	5.801	6.259

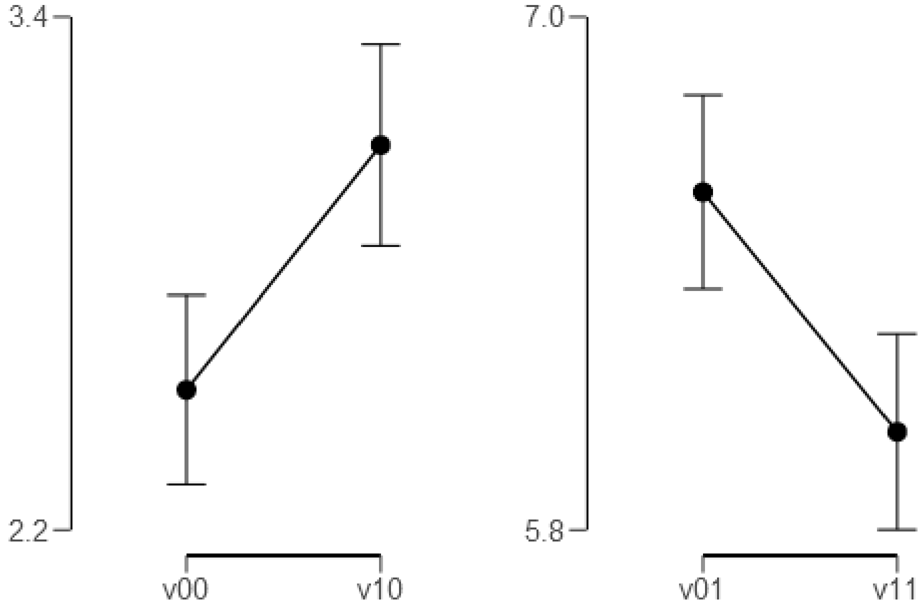


Figure 54. Difference between means per condition with associated 95% Bayesian credible intervals.

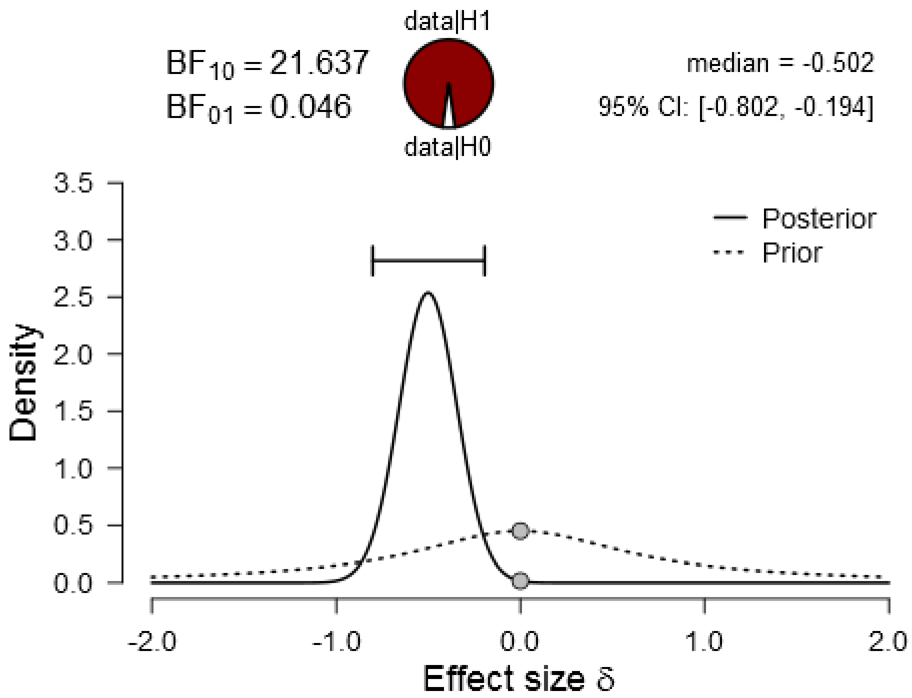


Figure 55. Prior and posterior plot for the difference between V_{00} vs. V_{10}.

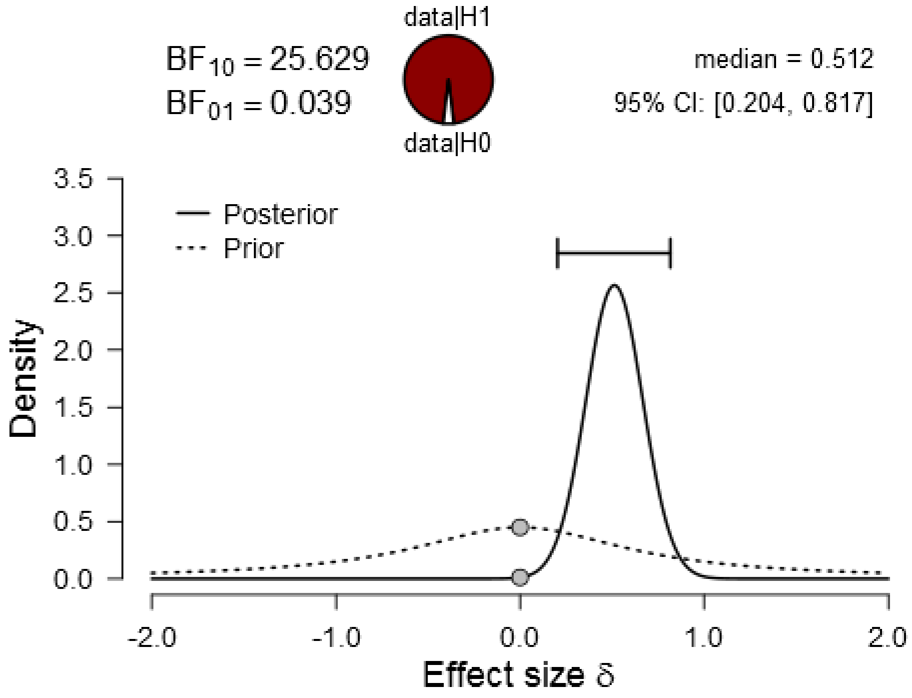


Figure 56. Prior and posterior plot for the difference between V_{01} vs. V_{11}.

We then followed-up the Bayes Factor analysis with a Bayesian parameter estimation procedure using MCMC methods in order to obtain precise posterior intervals. The BPE approach allows draw sensible inferences based on the previously discussed HDI/ROPE algorithm. The statistical inferential decisions based on Bayesian parameter estimation and Bayes Factor analysis do not necessarily converge, that is, they can lead to different conclusions.

4.4.3 Bayesian a posteriori parameter estimation using Markov chain Monte Carlo methods

As in in the previously reported experiments, we utilised Bayesian parameter estimation techniques based on MCMC simulation methods to obtain precise estimates of θ,. Specifically, the primary desideratum of this analysis was to obtain an accurate estimate of posterior characteristics, i.e., $p(\mu_1, \sigma_1, \mu_2, \sigma_2, \nu|D)$. The numerous significant advantages of this approach have been adumbrated in the previous chapters. We utilised the exact same model as specified in Experiment 1. Therefore, we will skip the detailed model specifications and immediately present the results in the following subsections, starting with the convergence diagnostics which evaluate whether the stationary equilibrium distribution π of the Markov Chain had been reached by our computations.

4.4.3.1 MCMC analysis and convergence diagnostics

The convergence diagnostics indicated that the equilibrium distribution π had been reached. A summary is provided in Appendix C4and we refer to Experiment 1 for an explanation of the various diagnostic criteria. Detailed convergence diagnostics for all parameters can be found in Appendix D. We thus proceeded with the analysis of the posterior distribution which is reported in the following subsection. $\hat{R}$ (Rhat, the potential scale reduction factor) had a value of 1, indicating that the chain reached π.

4.4.3.2 Markov chain Monte Carlo simulation output analysis and convergence diagnostics for experimental conditions V_{00} and V_{10}

After fitting our model, using the Bayesian parameter approach, we obtained a distribution of credible values the pertinent parameters. A numerical summary is given in Table 25 and a comprehensive synopsis is given in Figure 57.

Table 25

Numerical summary of the Bayesian parameter estimation for the difference between means for experimental condition V_{00} vs. V_{10} with associated 95% posterior high density credible intervals.

	mean	median	mode	HDI%	HDIlo	HDIup	compVal	%>compVal
mu	-0.564	-0.564	-0.557	95	-0.908	-0.231	0	0.079
sigma	1.483	1.477	1.458	95	1.226	1.750		
nu	39.002	30.709	15.903	95	2.794	98.714		
log10nu	1.473	1.487	1.509	95	0.815	2.080		
effSz	-0.384	-0.383	-0.389	95	-0.624	-0.151	0	0.079

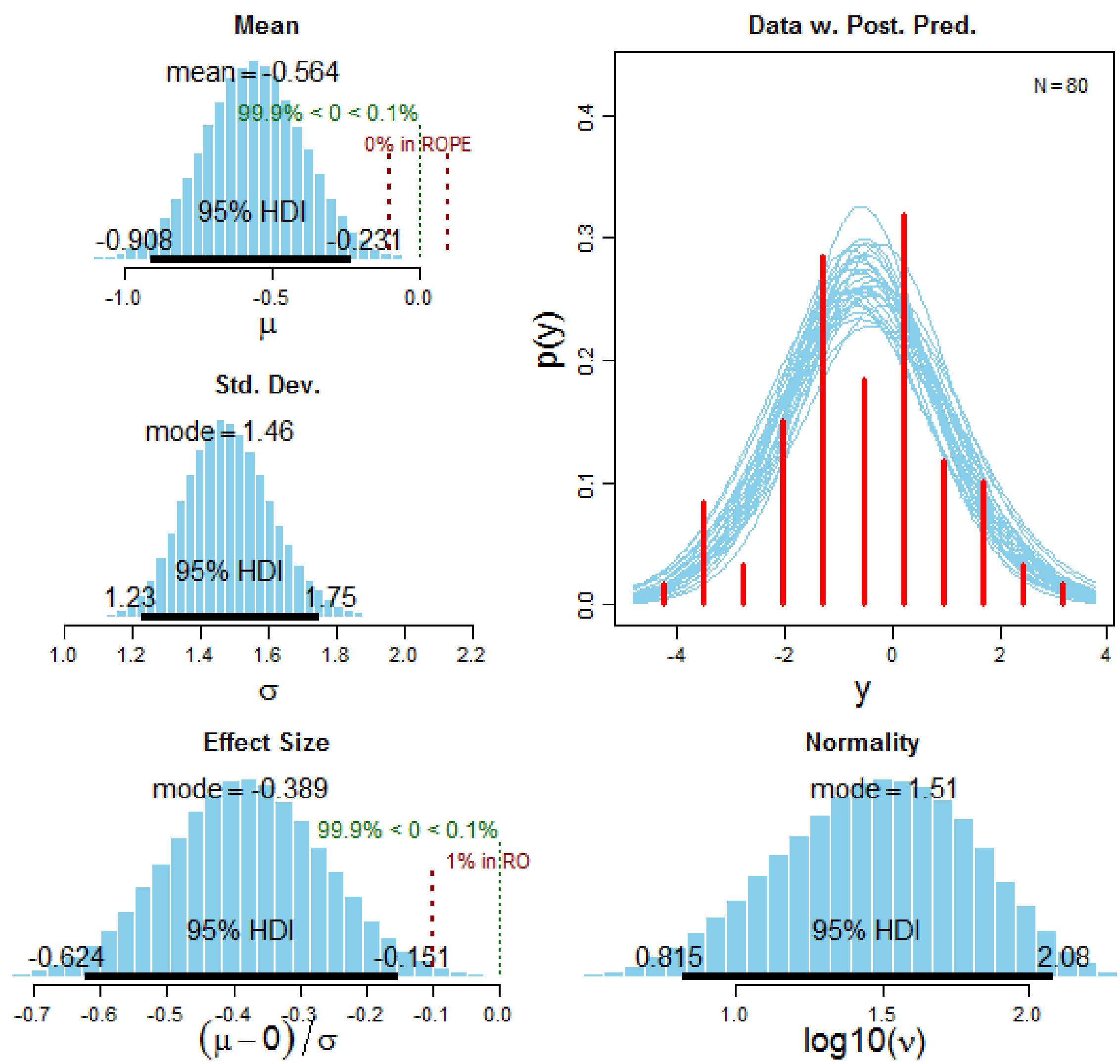


Figure 57. Visual summary of the Bayesian parameter estimation for the difference between means for experimental condition V_{00} vs. V_{01} with associated 95% HDIs and a ROPEs ranging from [-0.1, 0.1].

Left panel: Posterior distribution of the difference between means with associated 95% high density credible intervals and ROPE [-0.1,0.1], the standard deviation of the estimated difference and the corresponding effect size δ with its associated ROPE ranging from [-0.1,0.1] and 95% HDI. Right panel: Posterior predictive plot (n=30) for the mean difference. The normality parameter $\log_{10}(\nu)$ with accompanying 95% HDI.

4.4.3.3 Markov chain Monte Carlo simulation output analysis and convergence diagnostics for experimental conditions V_{01} and V_{11}

Table 26 summarises the convergence diagnostics and the results for the second pairwise comparison (V_{01} and V_{11}) are given in Table 27. A complete summary of the analysis is provided in Figure 58.

Table 26

MCMC convergence diagnostics based on 100002 simulations for the difference in means between experimental condition V_{01} vs. V_{11}.

	Rhat	n.eff
mu	1.000	61128
nu	1.001	18842
sigma	1.000	38649

Table 27
Numerical summary of the Bayesian parameter estimation for the difference between means for experimental condition V_{01} vs. V_{11} with associated 95% posterior high density credible intervals.

	mean	median	mode	HDI%	HDIlo	HDIup	compVal	%>compVal
mu	0.577	0.577	0.564	95	0.248	0.901	0	100
sigma	1.414	1.409	1.404	95	1.158	1.682		
nu	36.293	27.759	13.043	95	2.652	94.768		
log10nu	1.429	1.443	1.484	95	0.757	2.072		
effSz	0.412	0.410	0.411	95	0.167	0.664	0	100

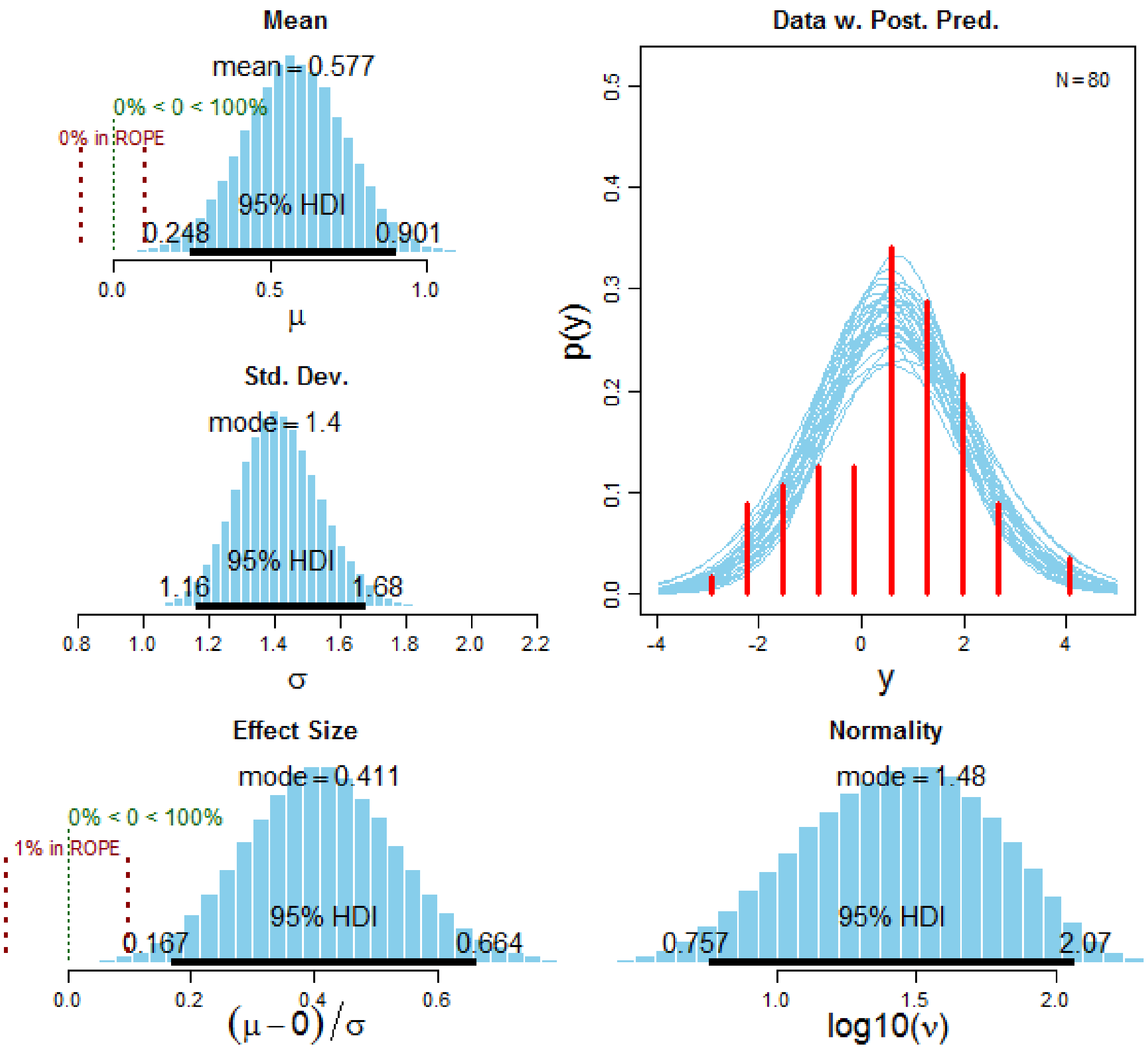


Figure 58. Visual summary of the Bayesian parameter estimation for the difference between means for experimental condition V_{10} vs. V_{11} with associated 95% HDIs and a ROPEs ranging from [-0.1, 0.1]. Left panel: Posterior distribution of the difference between means with associated 95% high density credible intervals and ROPE [-0.1,0.1], the standard deviation of the estimated difference and the corresponding effect size δ with its associated ROPE ranging from [-0.1,0.1] and 95% HDI. Right panel: Posterior predictive plot (n=30) for the mean difference. The normality parameter $\log_{10}(v)$ with accompanying 95% HDI.

4.5 Discussion

The results of this experiment replicated the findings of Experiment 1 and thereby supported the modality-nonspecificity and generalisability of our results. That is, the findings confirmed our *a priori* predictions and demonstrate noncommutativity effects in psychophysical auditory judgments similar to those found in the visual domain. Moreover, the results of the statistical analyses are in line with the general predictions formulated by Atmanspacher and colleagues (Atmanspacher, 2014, 2016; Atmanspacher & Römer, 2012b). The implications of these empirical results will be discussed in a broader context in the general discussion section.

CHAPTER 5. EXPERIMENT #4: CONSTRUCTIVE MEASUREMENT EFFECTS IN SEQUENTIAL AUDITORY PERCEPTUAL JUDGMENTS

5.1 Experimental purpose

The primary purpose of this experiment was to cross-validate the empirical findings obtained in Experiment 2 in a different sensory modality in order to establish the generalisability (i.e., modality-nonspecificity) of the results obtained in Experiment 2. Therefore, the experimental designs were isomorphic with the exception that auditory stimuli were used instead of visual stimuli. The methodological correspondence between experiments thus enabled direct comparability of results (i.e., empirical commensurability).

5.2 *A priori* hypotheses

The hypotheses were identical to those formulated in Experiment 2 and were likewise in accordance with predictions derived from the relevant quantum cognition literature (Atmanspacher, 2014a, 2016; Atmanspacher & Römer, 2012; Z. Wang et al., 2013).

H_1: Measuring subjectively perceived loudness of the high intensity auditory stimuli first (i.e., binary measurement condition) results in a decrease in the subsequent judgment for the low intensity stimuli as compared to the opposite order.

H_2: Measuring the loudness of the low intensity auditory stimuli first results in an increase in the subsequent judgment relative to opposite order.

In symbolic form the null and alternative hypotheses are expressed as follows:

In symbolic form expressed as follows:

$\mathrm{H}_1: \mu_{V00} > \mu_{v01}$

$\mathrm{H}_2: \mu_{V10} < \mu_{V11}$

where

V_{00} = high intensity stimuli → low intensity stimuli (singular measurement)

V_{01} = high intensity stimuli → low intensity stimuli (binary measurement)

V_{10} = low intensity stimuli → high intensity stimuli (singular measurement)

V_{11} = low intensity stimuli → high intensity stimuli (binary measurement)

The main goal of this audiometric psychophysics experiment was thus to investigate the constructive influence of an intermediate introspective psychophysical judgement on a subsequent one. As pointed out before, the constructive role of measurements is pivotal to the basic tenets of quantum mechanics and similar effects have been documented in various cognitive domains (e.g., Pothos & Busemeyer, 2013).

5.3 Method

5.3.1 Participants and Design

The experiment was conducted in the computer laboratory at Manipal University Jaipur in India. Ethical approval was obtained from the head of the Department of Psychology, Professor Geetika Tankha who supervised this study.

One hundred undergraduate students participated in this study (62 women and 38 men, ages ranging between 18 and 25 years, M_{age} = 19.91; SD_{age} = 2.35). Students were recruited via email and flyers which were distributed on campus. As in the previous experiments, a custom-made website was designed in HTML was utilised to advertise the study in an attractive way to the student population. All participants were financially reimbursed for their participation (₹800)[148].

5.3.2 Apparatus and materials

We utilised the same stimuli as in Experiment 2 for this audiometric experiment, i.e., two auditory stimuli of the same frequency but with varying intensity levels (for details see the methods section of Experiment 2).

As in Experiment 2, the entire experiment was implemented in PsychoPy. The associated Python source-code can be accessed under the following URL as a compressed ZIP archive: http://irrational-decisions.com/?page_id=618

5.3.3 Experimental Design

The structure of the experiment was a 2(measurement condition: singular rating vs. binary measurement) x 2(stimulus order: high intensity → low intensity vs. low intensity → high intensity) repeated measures design. The dependent measure was the condition dependent intensity rating which was recorded on a VAS as in our previous experiments.

[148] Due to the extremely chaotic demonetization of all ₹500 and ₹1,000 banknotes of the Mahatma Gandhi Series the payment was delayed for approximately half of the participants. The decision of the government was unforeseen and caused serious social problems as money became a scarce resource overnight. It was impossible to withdraw any “new” money from banks for several days which caused an *extremely* chaotic situation in the whole country.

5.3.4 Procedure

Before the commencement of the study, participants were briefed and accorded informed consent. Subsequently, participants were seated in front of a personal computer and received further instructions.

5.3.5 Sequential auditory perception paradigm

The experimental design was identical to Experiment 2 and we refer to the methods section for details to avoid repetition. The only difference was that we switched the sensory modality, i.e., we utilised auditory stimuli instead of visual stimuli. A diagrammatic depiction of the temporal sequence of events within two successive experimental trials is depicted in Figure 59.

The within-trial sequence of events was as follows: Initially, a white fixation cross was displayed on a black background until a manual response (single left mouse-click) was emitted. The following instructions were presented to participants: "*New trial: Please fixate the cross with your eyes and click the mouse when you are ready*". Next, an auditory stimulus of either high or low intensity was binaurally presented (via headphones). The stimulus was then replaced by a rating request or no rating request, (i.e., binary vs. singular measurement condition) which was presented until a response was emitted (either a rating on the VAS or a mouse-click response, depending on the respective experimental condition). After that, the second auditory stimulus appeared for the same temporal duration followed by the final rating request. In sum, participants completed a total of 600 experimental trials.

Upon completion of the experiment, participants were debriefed and were given the possibility to ask questions concerning the purpose and theoretical background of the study. Finally, participants were thanked for their cognitive efforts, financially reimbursed, and released.

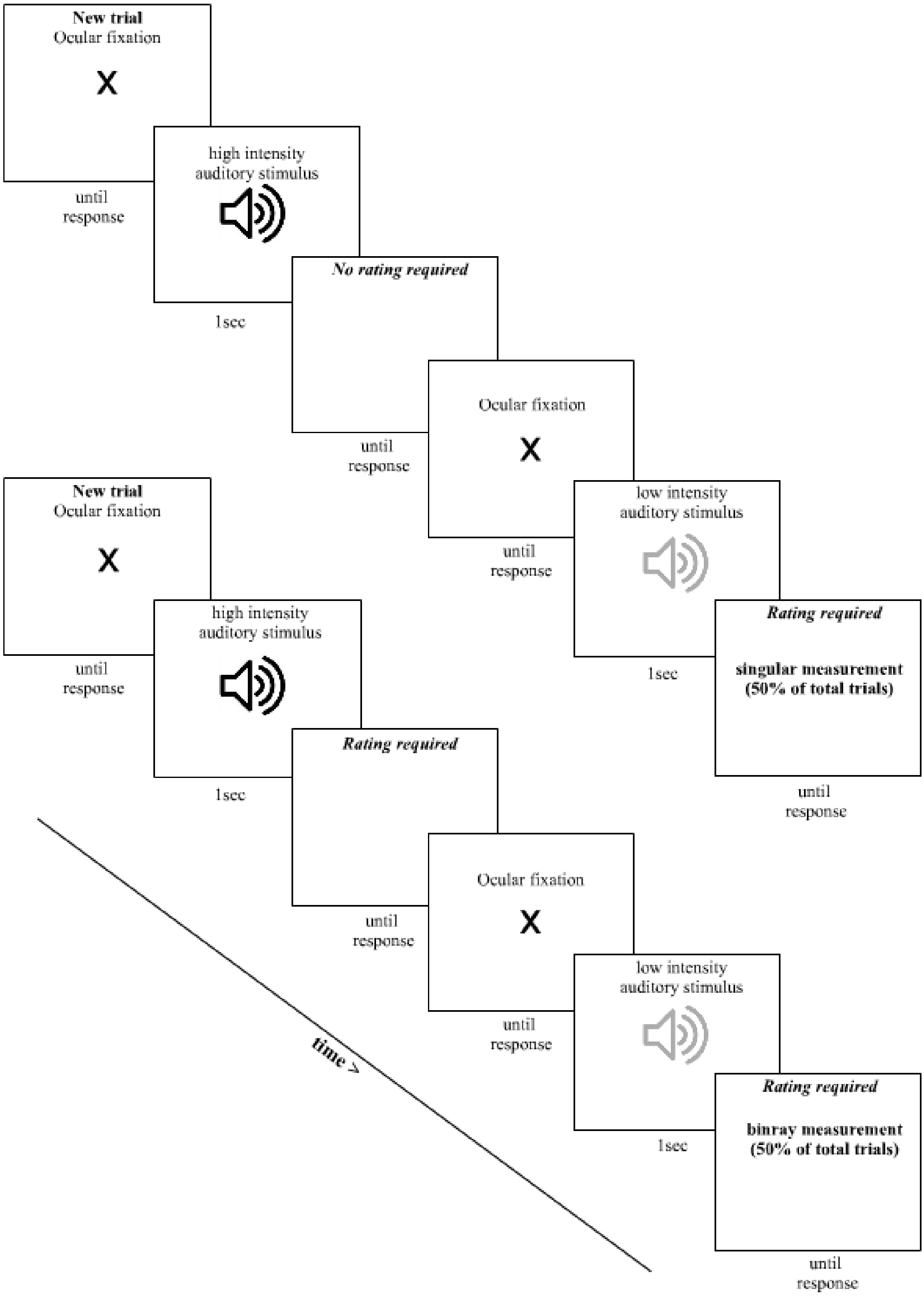


Figure 59. Diagrammatic representation of the temporal sequence of events within two successive experimental trials in Experiment 4.

5.4 Statistical Analysis

As in the previous statistical analyses, we employed various complementary inferential techniques to test our predictions. As pointed out before, statistical methods are currently rapidly evolving. Although still widely used (and taught), NHST has been conclusively dismantled as a statistical chimera. It is widely misinterpreted by professional researchers, i.e., more than 80% of statistics lecturers at universities are unable to interpret the most simple NHST analysis correctly (Haller & Krauss, 2002; Oakes, 1986). Novel methods have been proposed by the APA (Cumming, 2014) but they nevertheless do not emphasise the Bayesian alternatives emphatically enough (Kruschke & Liddell, 2017b). That is, the APA primarily tries to reinforce the usage of confidence intervals and effect sizes, both of which are ultimately based on frequentist principles. Furthermore, it has been experimentally demonstrated that confidence intervals are also widely misinterpreted by the vast majority of professional researchers in various academic disciplines (Hoekstra, Morey, Rouder, & Wagenmakers, 2014). Therefore, we utilised Bayesian inferential statistics in addition to the conventional frequentist methods in our analyses. However, the Bayesian camp is subdivided. While some argue for the adequacy of the Bayes Factor (Dienes, 2014, 2016; Richard D. Morey & Rouder, 2011; Rouder, Morey, Verhagen, Swagman, & Wagenmakers, 2017), other emphasize the numerous advantages which Bayesian parameter estimation based on Markov Chain Monte Carlo methods has over and above the more straightforward Bayes Factor analysis (Kruschke, 2014; Kruschke & Liddell, 2015; Kruschke et al., 2017). Therefore, we utilise both approaches in order to cross-validate our statistical results in different mathematical frameworks.

5.4.1 Frequentist analysis

We first tested the underlying distributional assumption and conducted several tests of normality (see Appendix E). We then proceeded to test our research hypotheses with a paired samples *t*-test (i.e., repeated measures *t*-test. The associated descriptive statistics are depicted in Table 28.

Table 28

Descriptive statistics for experimental conditions.

	N	**Mean**	**SD**	**SE**
v00	100	4.430	1.090	0.109
v01	100	3.910	1.020	0.102
v10	100	6.900	1.030	0.103
v11	100	7.370	1.070	0.107

Variable declarations:

V_{00}= high intensity stimuli → low intensity stimuli (singular measurement)

V_{01}= high intensity stimuli → low intensity stimuli (binary measurement)

V_{10}= low intensity stimuli → high intensity stimuli (singular measurement)

V_{11}= low intensity stimuli → high intensity stimuli (binary measurement)

Table 29

Shapiro-Wilk's W test of Gaussianity.

		W	p
v00	- v01	0.986	0.350
v10	- v11	0.993	0.896

Note. Significant results suggest a deviation from normality.

The *t*-test indicated significant differences between conditions. The first comparison indicated that V_{00} was rated significantly higher relative to V_{01}, $M_{\Delta}=0.52$; $t(99)=3.42$, $p<0.001$, 95%*CI* [0.22, 0.82]; Cohen's $d=0.34$, 95%*CI* for *d* [0.14, 0.54]. Conversely, V_{10} was rated significantly lower as compared to V_{11} $M_{\Delta}=-0.47$; $t(99)=-3.10$, $p=0.003$, 95%*CI* [-0.77, -0.18]; Cohen's $d=-0.31$, 95%*CI* for *d* [-0.51, 0.11]. A comprehensive tabular summary including the Vovk-Sellke maximum *p*-ratio (Sellke et al., 2001; Vovk, 1993) is provided in Table 30. Moreover, the results are visualised in Figure 60 and the distributional properties are depicted in Figure 61.

In sum, the results supported our initial predictions and provided a second conceptual cross-validation of the findings reported by White, Photos, & Busemeyer (White et al., 2014b).

A comprehensive synopsis of the results including the Vovk-Sellke maximum *p*-ratio (Sellke et al., 2001; Vovk, 1993) is provided under the following URL as a HTML-file: http://irrational-decisions.com/phd-thesis/frequentist-analysis-exp4.html

In addition we report p_{rep}, i.e., the probability of replicating the results upon an exact replication as introduced by Peter Killeen (2005a) as an alternative to conventional *p* values (see Appendix E14).

A comprehensive summary of the results is provided under the following URL:

http://irrational-decisions.com/phd-thesis/exp2/frequentist_t-test_exp4/

In the next section, we repeated the analysis using Bayesian parameter estimation via Markov chain Monte Carlo sampling.

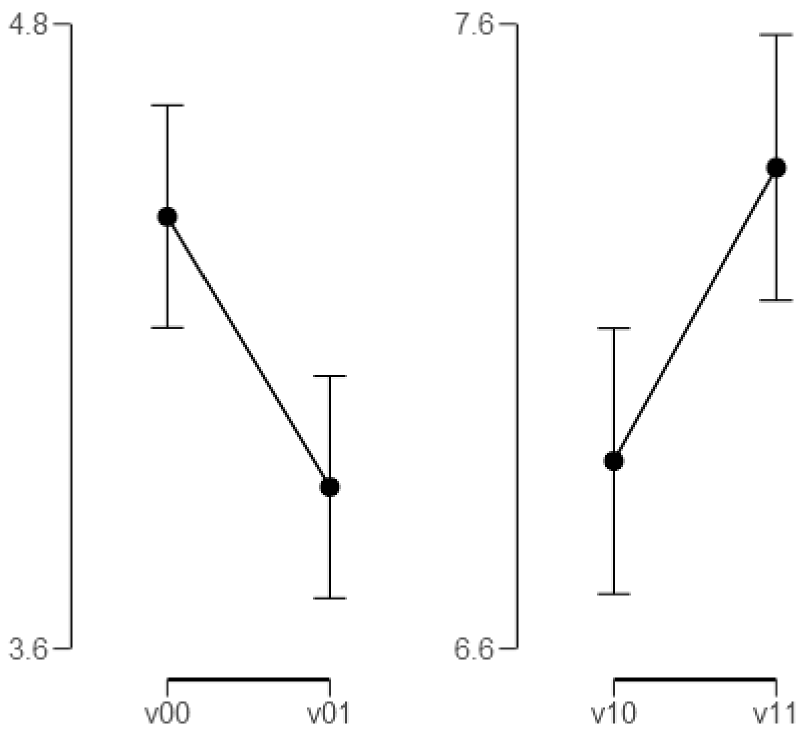


Figure 60. Visual summary of differences between means with associated 95% confidence intervals.

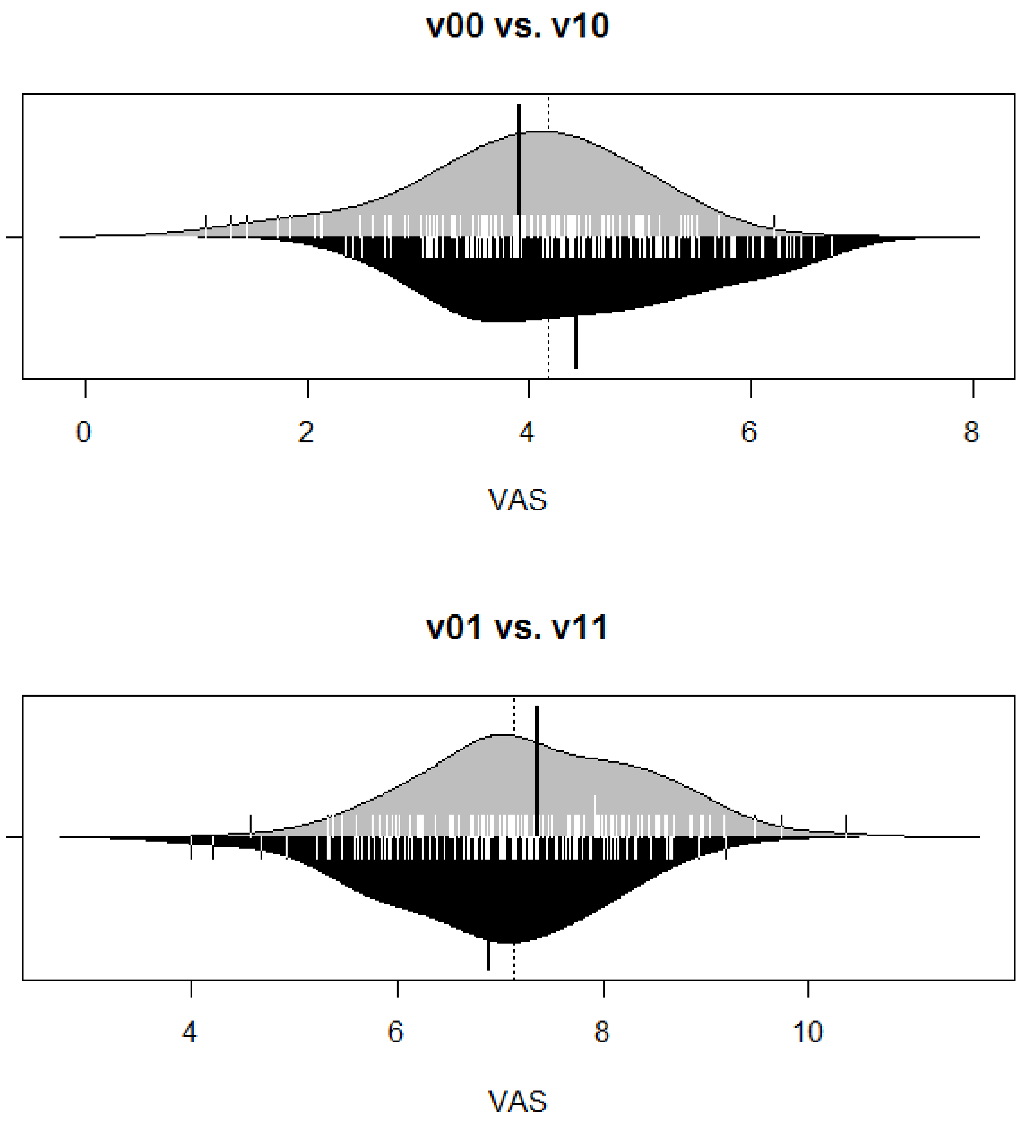


Figure 61. Beanplots depicting the differences in means and various distributional characteristics of the dataset.

Table 30

Paired samples t-tests and nonparametric Wilcoxon signed-rank tests.

								95% CI for Location Parameter			95% CI for Effect Size	
	Test	**Statistic**	**df**	**p**	**VS-MPR***	**Location Parameter**	**SE Difference**	**Lower**	**Upper**	**Effect Size**	**Lower**	**Upper**
v00 - v01	Student	3.418	99	9.169e - 4	57.360	0.520	0.152	0.218	0.822	0.342	0.139	0.543
	Wilcoxon	3439.000		0.002	34.201	0.508		0.209	0.827	0.362	0.152	0.541
v10 - v11	Student	-3.102	99	0.003	24.525	-0.470	0.152	-0.771	-0.169	-0.310	-0.510	-0.109
	Wilcoxon	1688.000		0.004	16.570	-0.467		-0.774	-0.145	-0.331	-0.516	-0.118

* Vovk-Sellke Maximum p -Ratio: Based on the p -value, the maximum possible odds in favor of H_1 over H_0 equals 1/(-e p log(p)) for $p \leq .37$ (Sellke, Bayarri, & Berger, 2001).

Note. For the Student t-test, location parameter is given by mean difference d ; for the Wilcoxon test, effect size is given by the Hodges-Lehmann estimate.

Note. For the Student t-test, effect size is given by Cohen's d ; for the Wilcoxon test, effect size is given by the matched rank biserial correlation.

5.4.2 Bayes Factor analysis

The Bayesian model we specified was isomorphic to Experiment 2, i.e., we specified the same noncommittal "objective Bayes" Cauchy priors (cf. Gronau et al., 2017).

H_1: $\delta \sim \text{Cauchy}(0,r)$

The Bayes Factor for the first comparison (experimental condition V_{00} vs. V_{01}) resulted in a Bayes Factor of $BF_{10} \approx 24.05$, i.e., $P(D \mid H_1) \approx 24.05$ and conversely $P(D \mid H_0) \approx 0.04$. The BF for the second contrast (V_{10} vs. V_{11}) was $BF_{10} \approx 9.71$, i.e., and its reciprocal was $P(D \mid H_0) \approx 0.10$. The results (with associated errors) are depicted in Table 14. According to Jeffreys' interpretational schema, the two Bayes Factors provide strong to moderate-strong evidence for H_1. Descriptive statistics and the associated 95% Bayesian credible intervals are given in Table 15. In addition, the results are visualised in Figure 62. A complete summary of the results of the Bayes Factor analysis is available under the following URL: http://irrational-decisions.com/phd-thesis/bayesfactor-analysis-exp4.html

In addition, we uploaded the underlying JASP analysis script to facilitate analytical reviews as suggested by Sakaluk, Williams, & Biernat (2014): http://irrational-decisions.com/phd-thesis/analysis-script-exp4.jasp

Table 31

Bayes Factors for both orthogonal contrasts.

		BF_{10}	error %
v00	- v01	24.050	6.998e -7
v10	- v11	9.707	1.725e -6

Table 32

Descriptive statistics with associated 95% Bayesian credible intervals.

					95% Credible Interval	
	N	**Mean**	**SD**	**SE**	**Lower**	**Upper**
v00	100	4.430	1.090	0.109	4.214	4.646
v01	100	3.910	1.020	0.102	3.708	4.112
v10	100	6.900	1.030	0.103	6.696	7.104
v11	100	7.370	1.070	0.107	7.158	7.582

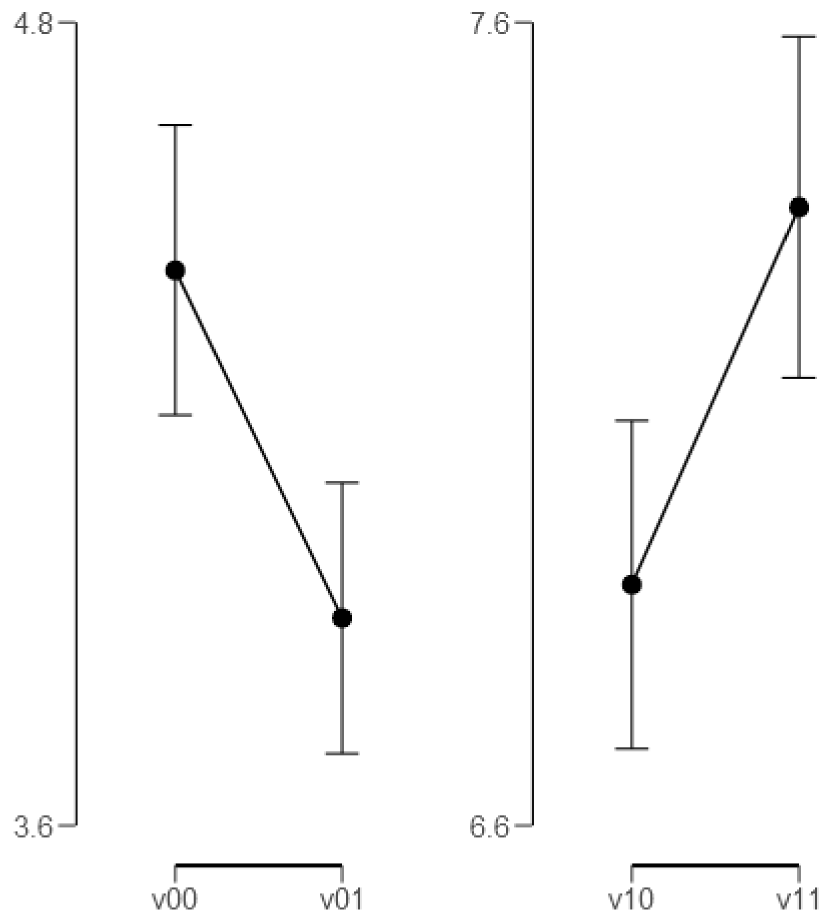


Figure 62. Means per condition with associated 95% Bayesian credible intervals.

A visual summary of the most important analytic results is given in Figure 63 and Figure 64. The figures are composed of: 1) a visualisation the prior distribution of the effect sizes, 2) the associated posterior distributions, 3) the associated 95% Bayesian credible intervals, 4) the posterior medians, 5) the Bayes Factors, 6) the associated Savage–Dickey density ratios[149] (E. J. Wagenmakers et al., 2010), 7) pie-charts of the Bayes Factor in favour of H_1.

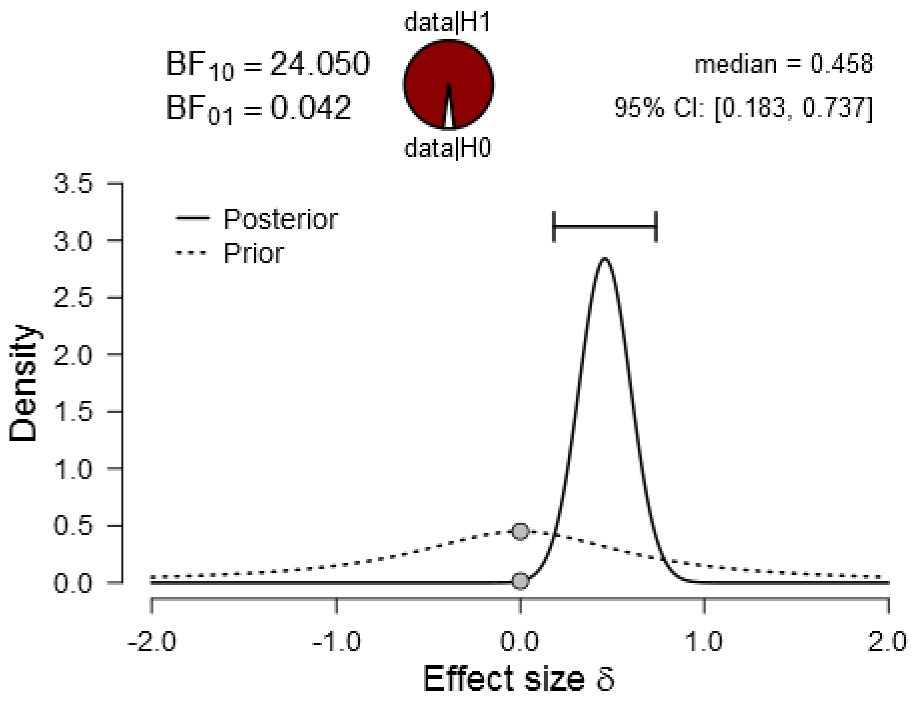


Figure 63. Prior and posterior plot for the difference between V_{00} vs. V_{01}.

[149] For an interactive visualisation see http://irrational-decisions.com/?page_id=2328

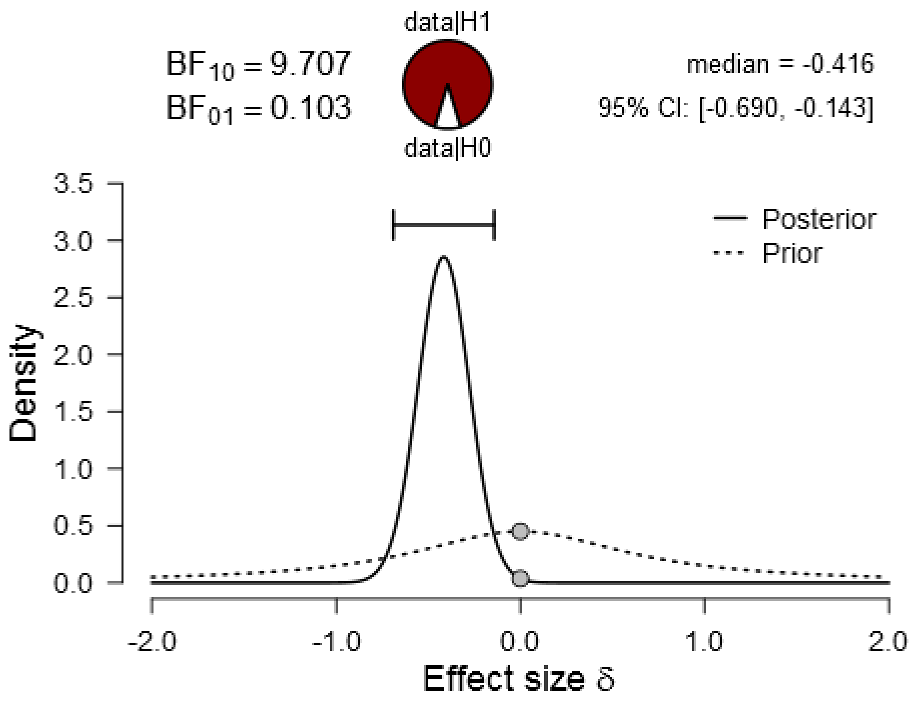


Figure 64. Prior and posterior plot for the difference between V_{10} vs. V_{11}.

As in Experiment 2, we performed Bayes Factor robustness checks for a range of Cauchy priors per comparison. The results indicated that the evidence for H_1 was robust under various parametrisations. For the first contrast (V_{00} vs. V_{01}) the maximum BF was obtained at $r \approx 0.29$ (max $BF_{10} \approx 32.26$) and for the second contrast (V_{10} vs. V_{11}) at $r \approx 0.26$ (max $BF_{10} \approx 14.03$). Details of the robustness check are given in Figure 65 and Figure 66, respectively. Similar to the previous analyses, we computed a sequential Bayes Factor analysis to investigate the accrual of evidence in favour of over time. The results per comparison are visualised in Figure 67 and Figure 68, respectively. It is noteworthy that for the first comparison (V_{00} vs. V_{01}), there was a peak around n=50, followed by a decline of the strength of evidence. However, in the subsequent trials evidence increased again steadily and reached its maximum value around n=95, viz., "strong evidence" for H_1 according to Jeffreys' heuristic interpretational schema (Jeffreys, 1961). For the second comparison, evidence in favour of H_1 became only available after n=90 (ending up on the border between moderate and strong evidence for H_1).

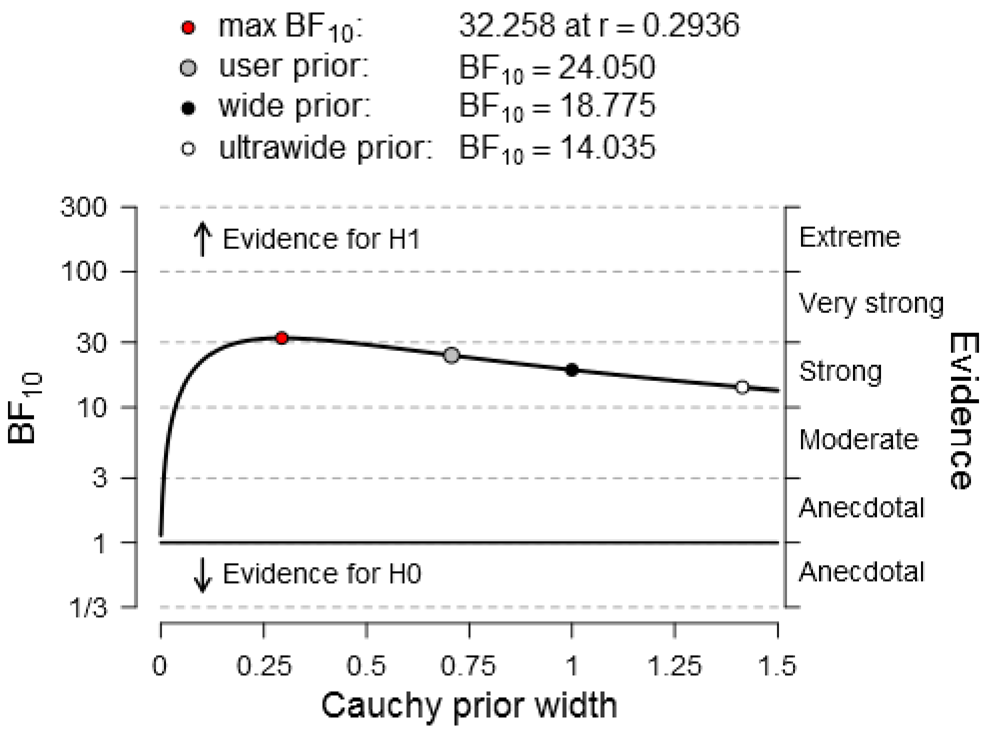


Figure 65. Bayes Factor robustness check for condition V_{00} vs. V_{10} using various Cauchy priors.

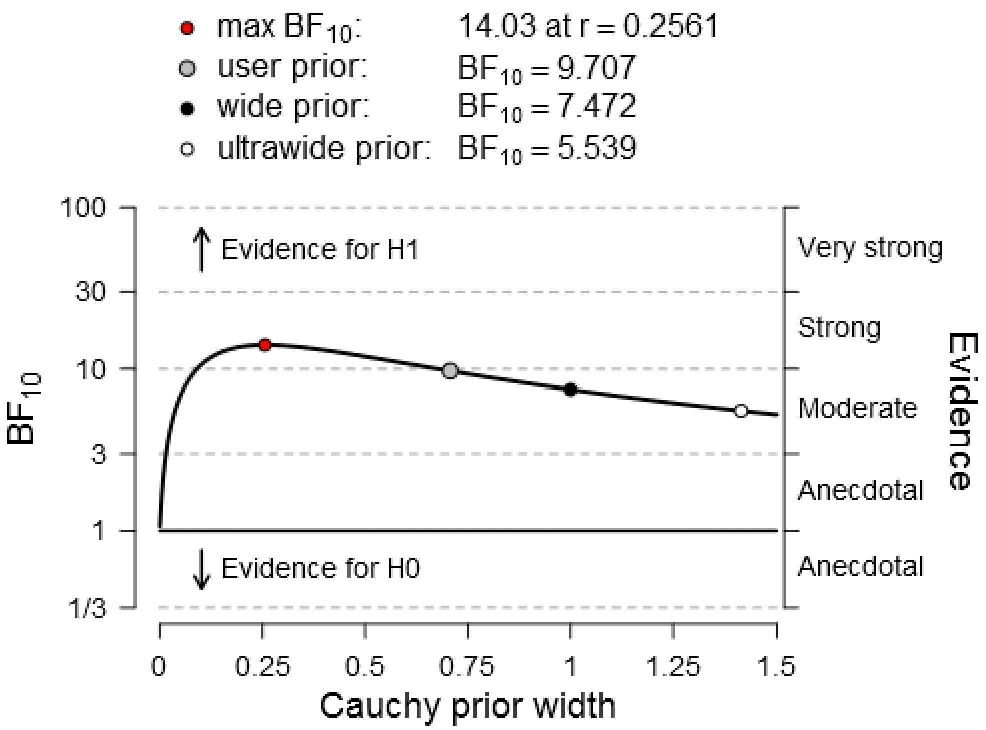


Figure 66. Bayes Factor robustness check for condition V_{01} vs. V_{11} using various Cauchy priors.

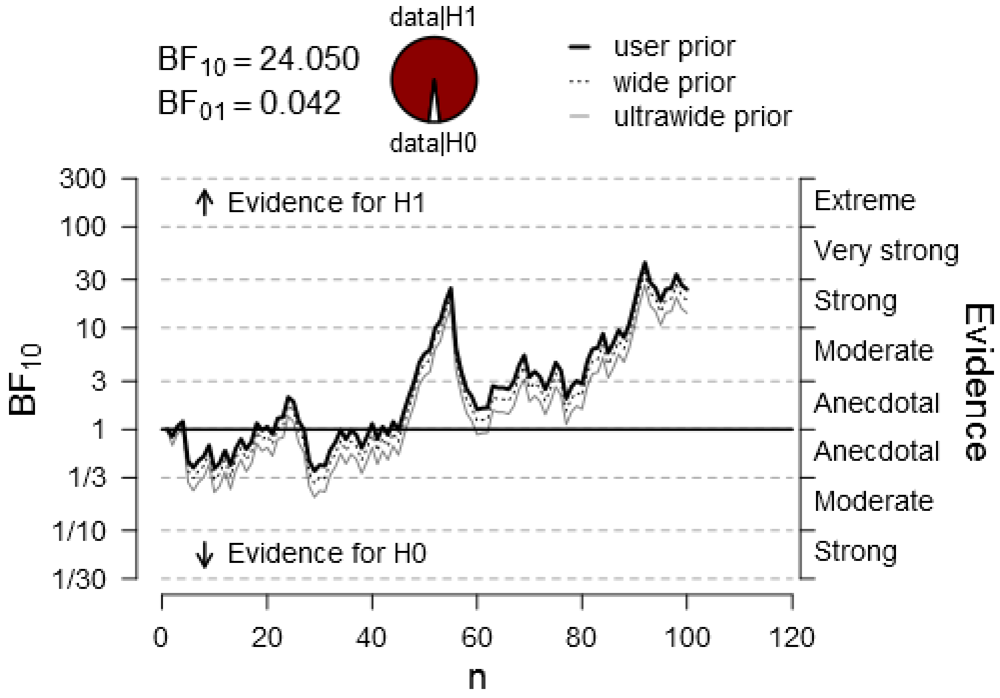


Figure 67. Sequential analysis depicting the accumulation of evidence as n accumulates over time (for experimental condition V_{00} vs. V_{10}).

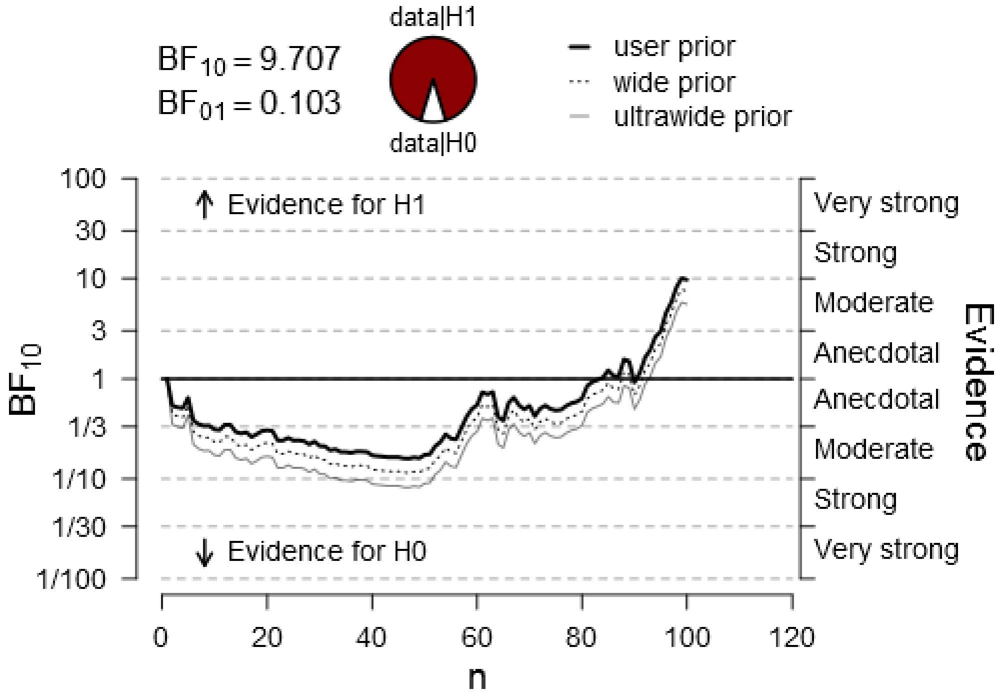


Figure 68. Sequential analysis depicting the accumulation of evidence as n accumulates over time (for experimental condition V_{00} vs. V_{10}).

5.4.3 Bayesian a posteriori parameter estimation using Markov chain Monte Carlo methods

This section reports the application Bayesian parameter estimation via Markov chain Monte Carlo (MCMC) methods to the data of Experiment 4. It has been demonstrated that MCMS methods are a very powerful approach to statistical analysis and inference (Gelman et al., 2004). Specifically, we conducted Bayesian analyses with computations performed by the Gibbs-sampler JAGS (Plummer, 2005). JAGS is a “flexible software for MCMC implementation” (Depaoli et al., 2016). We were particularly interested in measures of central tendency derived from the posterior distribution in order to evaluate differences between experimental conditions. However, we also estimated additional metrics (e.g., quantiles) of the posterior to gain a more complete picture.

5.4.3.1 Bayesian parameter estimation for the difference between experimental condition V_{00} vs. V_{01}

We utilised the same hierarchical Bayesian model as described in Experiment 2. That is, we specified the same priors on all parameters and performed the simulation with the same specifications. As in the previous analysis, we performed the MCMC simulation with 100000 iterations, 500 adaptation steps, and 1000 burn-in steps (no thinning, 3 Markov chains in parallel). We will first report the convergence diagnostics and we will then proceed to examine the posterior distributions.

5.4.3.2 Markov chain Monte Carlo simulation output analysis and convergence diagnostics

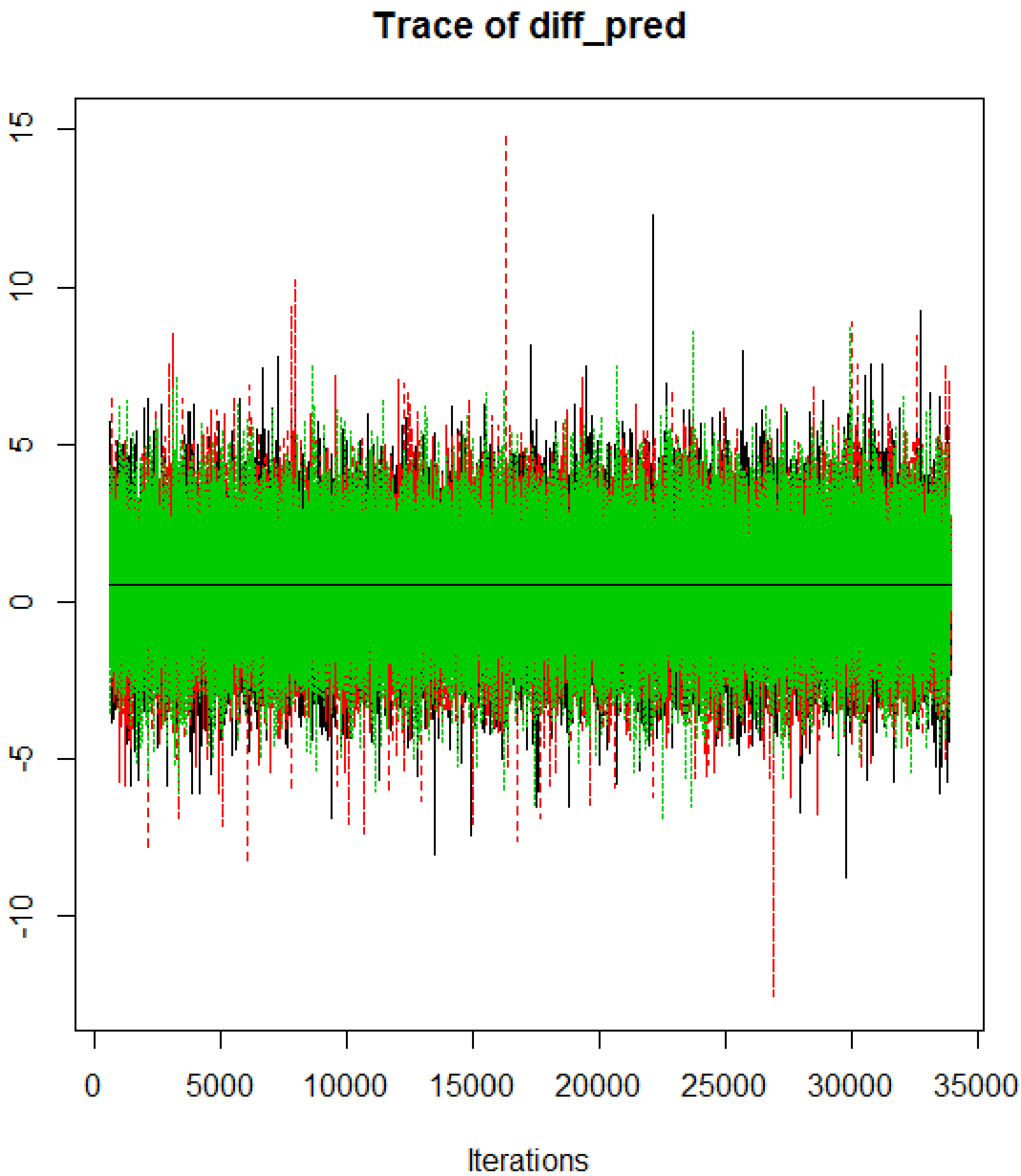


Figure 69. Trace plot of the predicted difference between means for one of the three Markov Chains. The patterns suggest convergence to the equilibrium distribution π.

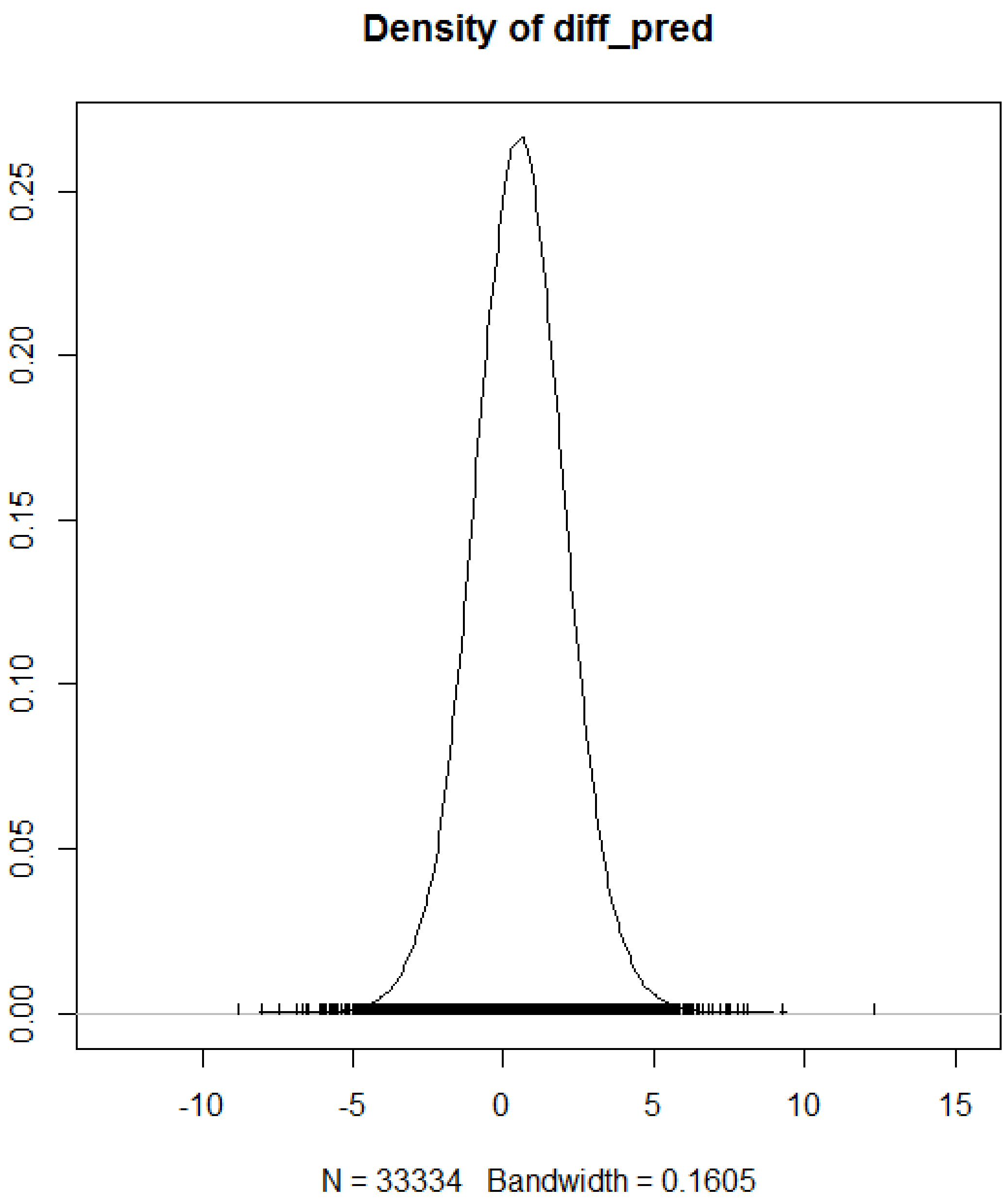


Figure 70. Density plot for the predicted difference between means.

Table 33

Summary of selected convergence diagnostics.

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

             mean     sd mcmc_se  n_eff  Rhat
mu_diff     0.524  0.182   0.001  65510 1.000
sigma_diff  1.466  0.143   0.001  45218 1.000
nu         37.497 29.840   0.214  19470 1.001
eff_size    0.361  0.129   0.001  65616 1.000
diff_pred   0.529  1.571   0.005 100633 1.000
```

Model parameters:

- μ_Δ (mu_diff): The estimated mean pairwise difference between experimental conditions
- σ_Δ (sigma_diff): the scale of the pairwise difference (a consistent estimate of SD when nu is large)
- ν (nu): The degrees-of-freedom for the bivariate *t* distribution fitted to the pairwise difference
- δ (eff_size): the effect size calculated as $(\mu_\Delta - 0)/\sigma_\Delta$.
- $\mu_{\Delta pred}$ (diff_pred): predicted distribution for a new datapoint generated as the pairwise difference between experimental conditions

Convergence diagnostics:

- mcmc_se (Monte Carlo Standard Error, MCSE): The estimated standard error of the MCMC approximation of the mean.
- n_eff (Effective Sample Size, ESS): A crude measure of effective MCMC sample size.
- Rhat (Shrink factor, $\hat{R}$): the potential scale reduction factor (at convergence, $\hat{R} \approx 1$).

Table 34

Results of Bayesian MCMC parameter estimation for experimental conditions V_{00} and V_{10} with associated 95% posterior high density credible intervals.

	mean	median	mode	HDI%	HDIlo	HDIup	compVal	%>compVal
mu	0.518	0.517	0.520	95	0.215	0.826	0	99.9
sigma	1.500	1.495	1.485	95	1.280	1.730		
nu	43.814	35.648	20.242	95	4.642	105.639		
log10nu	1.542	1.552	1.556	95	0.961	2.112		
effSz	0.347	0.346	0.346	95	0.142	0.561	0	99.9

As can be seen in Table 34, the posterior difference of means μ_{Δ} is ≈ 0.52 with a 95% HDI of [0.22, 0.83]. Taken together, the results of the Bayesian parameter estimation closely converge with the those of the Bayes Factor and frequentists analysis reported previously.

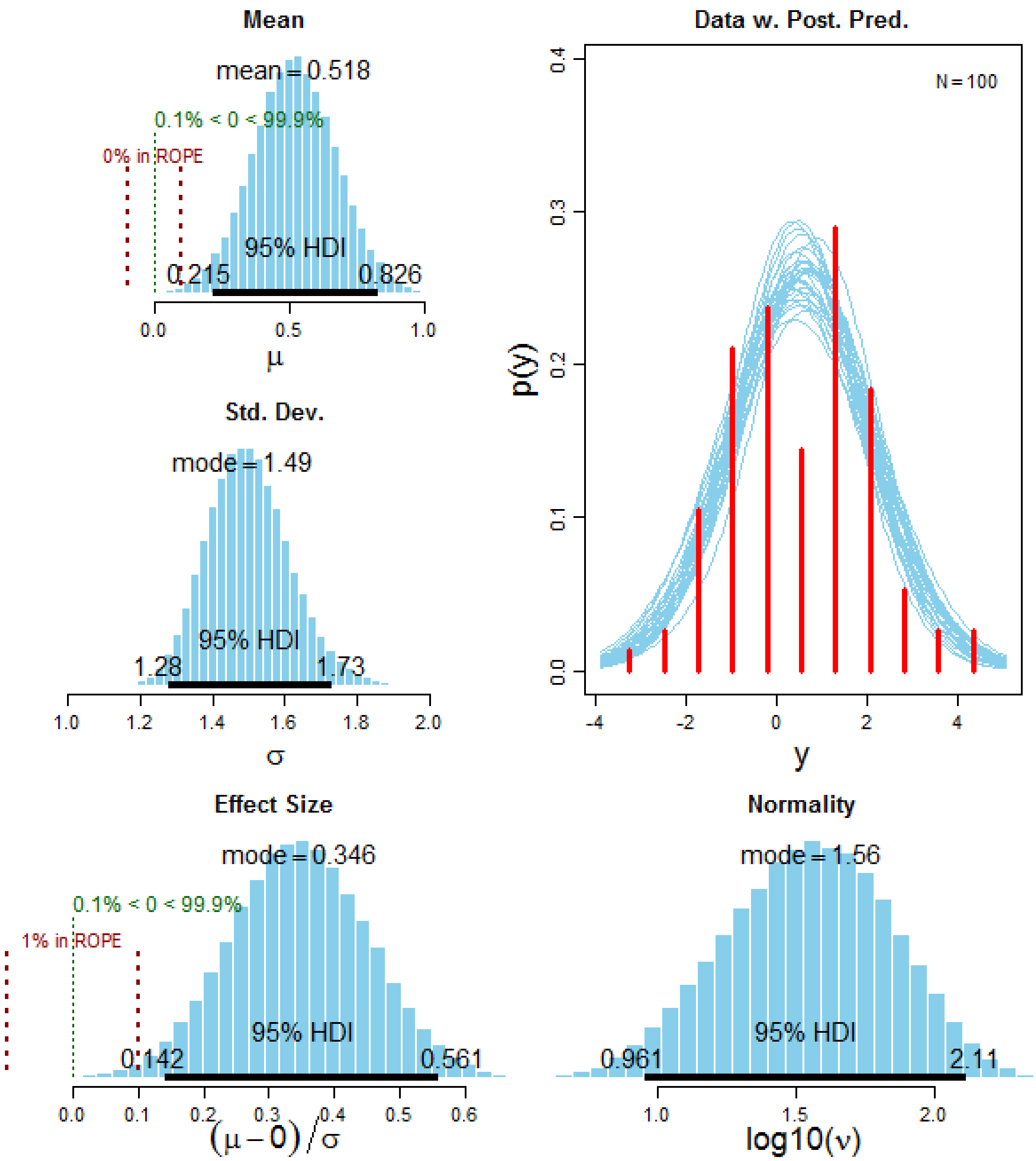


Figure 71. Comprehensive summary of the Bayesian parameter estimation.

Left panel: Posterior distribution of the difference between means (experimental condition V_{00} vs. V_{10}) with associated 95% high density credible intervals, and ROPE [-0.1,0.1] the standard deviation, of the estimated difference and the corresponding effect size. Right panel: Posterior predictive plot (*n*=30) for the mean difference. The normality parameter $\log_{10}(v)$ with accompanying 95% HDI.

Based on the ROPE/HDI decision algorithm described before (see Experiment 1), it can be concluded that the difference between experimental conditions is credible from a Bayesian parameter estimation point of view.

5.4.3.3 Bayesian parameter estimation for the difference between experimental condition V10 vs. V11

Table 35

Summary of selected convergence diagnostics.

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

             mean     sd mcmc_se n_eff  Rhat
mu_diff    -0.484  0.170   0.001 64751 1.000
sigma_diff  1.359  0.137   0.001 40827 1.000
nu         35.203 29.187   0.219 17750 1.001
eff_size   -0.360  0.131   0.001 60239 1.000
diff_pred  -0.482  1.468   0.005 99761 1.000
```

Table 36

Results of Bayesian MCMC parameter estimation for experimental conditions V_{10} and V_{11} with associated 95% posterior high density credible intervals.

```
          mean median   mode HDI%  HDIlo  HDIup compVal %>compVal
mu      -0.465 -0.466 -0.467   95 -0.768 -0.162       0     0.161
sigma    1.479  1.475  1.467   95  1.247  1.716
nu      39.423 31.058 15.418   95  3.315 98.429
log10nu  1.483  1.492  1.550   95  0.860  2.083
effSz   -0.317 -0.316 -0.312   95 -0.527 -0.108       0     0.161
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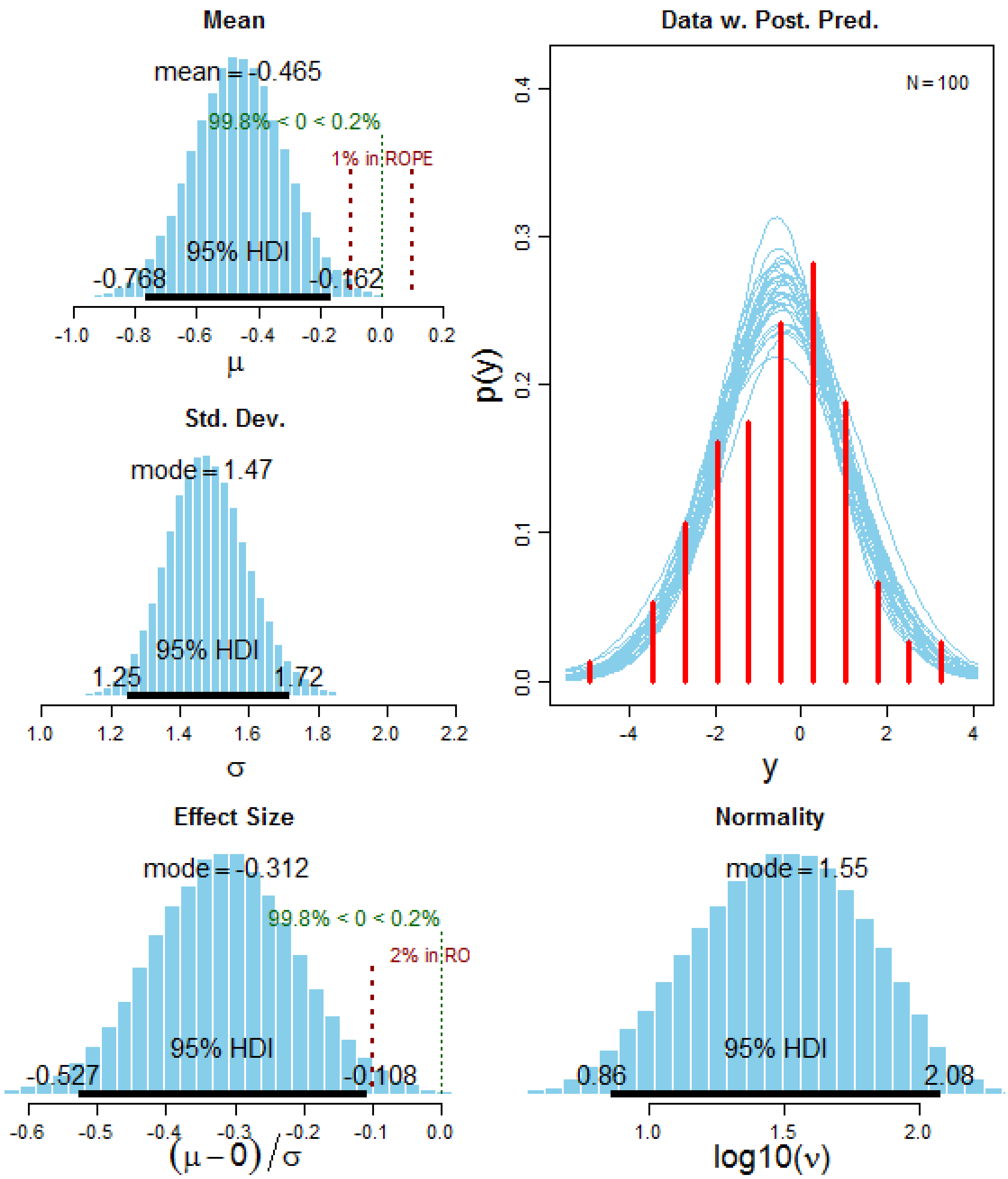

Figure 72. Posterior distributions for the mean pairwise difference between experimental conditions (V_{10} vs. V_{11}), the standard deviation of the pairwise difference, and the associated effect size, calculated as $(\mu_\Delta - 0)/\sigma_\Delta$.

It can be seen in Figure 72 that the ROPE for the difference between means does not overlap with the 95% HDI. It can thus be concluded that the difference of means in of *practical significance* from a Bayesian parameter estimation point of view. Moreover, the ROPE for δ did not overlap with the 95% HDI.

In sum, we concluded that the difference of means between experimental conditions V_{00} vs. V_{01} and V_{10} vs. V_{11} are credible. That is, both pairwise comparisons resulted in values that were credibly different from zero. Hence, we rejected H_0 for both hypotheses (i.e., $\mu_1 \neq \mu_2$). The conclusion is motivated by the position of the corresponding 95% equal-tail HDI for $\Delta_{(\mu1-\mu2)}$ relative to the region of practical equivalence. This conclusion is congruent with the inferential conclusion based on the previous frequentists NHST and Bayes Factor analysis.

5.5 Discussion

The results of Experiment 4 were isomorphic with those obtained in Experiment 2 and thus provided further support for the generalisability and modality-nonspecificity of our *a priori* predictions. Given that the experiments were directly commensurable, the present findings can be regarded as an empirical cross-validation and corroborate the predictions derived from the quantum cognition model (cf. White et al., 2015, 2014b). Moreover, our statistical analyses went beyond conventional (naïve) NHST (G Gigerenzer, 1998, 2004; Hoekstra et al., 2014; Kruschke, 2013) by combining various complementary mathematical/analytic frameworks (analytic triangulation). Our logical conclusions are therefore more firmly grounded than those which rely exclusively on orthodox (but logically invalid[150]) NHST.

[150] For a discussion of the widely misunderstood syllogistic logic behind NHST see Jacob Cohen's excellent contributions (Cohen, 1994, 1995) and section **Error! Reference source not found.**.

CHAPTER 6. GENERAL DISCUSSION

Taken together, our experimental findings lend empirical support to the predictions of the QP model in the domain of psychophysical measurements. Specifically, the results support the notion that cognitive processes can be modelled in terms of quantum principles such as 1) noncommutativity of psychological observables and 2) the constructive nature of psychophysical measurements. Furthermore, the results of our complementary statical analyses supported our *a priori* predictions unequivocally (which is not necessarily the case as NHST does not necessarily produce the same results as Bayes Factor analysis which in turn can theoretically significantly diverge from the inferential conclusions drawn from Markov chain Monte Carlo Bayesian parameter estimation methods).

Specifically, the results of Experiment 1 and 3 confirmed our *a priori* predictions in different sensory modalities (psychophysical noncommutativity effects in sequential photometric versus audiometric judgments). That is, the results of Experiment 3 replicated those obtained in Experiment 1 and thereby supported the modality-nonspecificity and generalisability of our results. The data are in line with the general predictions formulated by Atmanspacher and colleagues (Atmanspacher, 2014, 2016; Atmanspacher & Römer, 2012b). Moroever, the data obtained in Experiment 1 and 3 are homologous to the noncommutativity effects observed in the domain of political/attitudinal decisions discussed in the introduction. The data thus lends to support to the notion that noncommutativity is a fundamental feature of cognitive operations in humans. The domain-nonspecificity of noncommutativity is a very interesting finding and we will discuss potential fututure experiments along these lines in § 6.12. Particularly, it would be interesting to investigate whether the effects are not only generalisable across cognitive domains and perceptual modalities but also across the phylogenetic spectrum, for instance, in other non-human life-forms, like rodents, bacteria, fungi, et cetera. This kind of investigation would contribute to the establishment of fundamental (unifying) principles of decision-making across diverse domains and species. Such an interdisciplinary research program could be summarised under the header: “The phylogeny of decision-making principles”.

In sum, the findings support the generic prediction that “non-commuting operations must be expected to be the rule rather than the exception for operations on mental systems” (Atmanspacher, 2014a, p. 24). This statement has far-reaching implications for cognitive science (and many other disciplines) as commutativity is one of the unquestioned (taken-for-granted) axioms. In other words, Kolmogorovian/Boolean models are the de facto status quo in many scientific disciplines. Interestingly, the so called “status quo bias” (Kahneman, Knetsch, & Thaler, 1991) describes the human tendency to accept the status quo when faced with conflicting choice alternatives. We suggest that this bias also applies to decision between traditional Kolmogorovian/Boolean probability models and quantum models. That is, given the choice many researchers might think in terms of classical probabilities and disregard novel alternatives (cf. “loss aversion”). A cogent evolutionary/memetic argument could be developed for this class of cognitive biases which avoid “risky exploration” of novel territory. The need to belong and the physical danger associated with deviating from the group/herd significantly shaped our unconscious thought processes. Today humans no longer fear wild predators but deviating from the “memetic” group-norm is associated with other risks in the modern world. Rejecting “the default” (e.g., the predominant statistical model) is a difficult choice and neuroscientific imaging studies indicate that specific prefrontal-basal ganglia dynamics are involved in overcoming the status quo bias (S. M. Fleming, Thomas, & Dolan, 2010). However, for reasons of parsimony and concision we will only adumbrate the possibility of such an evolutionary/organic explanation which would necessarily involve a discussion of neuronal pathways associated with nonconformity and response suppression (cf. Bari & Robbins, 2013).

An open question concerns the exact nature of the mechanisms which underpin the cognitive mechanisms. Do the mechanisms which underlie noncommutativity take place at the level of the retina (i.e., at the photoreceptor level) or is noncommutativity caused by higher-order cognitive processes. In other words, where are the responsible processes neuroanatomically located? Do they take place higher-up in the processing hierarchy of the visual system, for example in higher-order association cortices (J. Y. Jung, Cloutman, Binney, & Lambon Ralph, 2017)? What role do top-down influences play in psychophysical noncommutativity? Are hierarchical neuropsychological models of visual and auditory perception appropriate? Are introspective psychophysical measurement effects caused by the collapse of the mental wave-function (Conte, Khrennikov, Todarello, Federici, & Zbilut, 2009) or is some other interference process involved? Our research cannot conclusively answer these important questions concerning the exact mechanisms which underlie perception. However, embedded in a broader empirical context (e.g., Z. Wang et al., 2013), our results corroborate the notion that perception is a constructive process and that introspective measurements of psychological observables change the cognitive variable(s) under investigation. In *sensu lato*, the concept of quantum indeterminacy thus appears to be pertinent for cognitive processes. In combination with other empirical findings (White et al., 2015, 2014b; Yearsley & Pothos, 2014), our results challenge a fundamental assumption which forms the basis of most cognitive models, namely that cognitive variables are always in a determinate state which can be objectively measured (i.e., interference-free). We propose the term "cognitive indeterminacy" as an analogon to quantum indeterminacy to demarcate this aspect of the QP model from “cognitive determinism” which form the mainly unquestioned basis of most cognitive and neuropsychological models (cf. Popper, 1950). The term cognitive indeterminacy implies that cognitive variables are undetermined unless they are measured. This account stands in direct contrast with cognitive determinism which stipulates the cognitive system is always in a fixed state which can theoretically be objectively measured without measurement-induced perturbation. The implications of this distinction are far reaching and deserve further systematic investigation. It has been noted before that “*behavioral scientists of all kinds are beginning to engage the issues of indeterminacy that plagued physics at the beginning of the twentieth century*” (Glimcher, 2005, p. 25) and the topic of (visual) indeterminacy has recently connected the arts with the sciences (Pepperell, 2006, 2011). The quantum physical concept of “counterfactual definiteness” appears thus relevant beyond physics and particularly for psychological measurements. Counterfactual definiteness refers to the ability to speak of the outcome of measurements that have not yet been carried out. In the words of Asher Peres representing the traditional Copenhagen interpretation: “unperformed experiments have no results” (A Peres, 1978). By contrast, in the context of the many-worlds interpretation of quantum mechanics (Everett, 2004; Tegmark, 2010; Tipler, 2000) it has been stated that "the many-worlds interpretation is not only counterfactually indefinite, it is factually indefinite as well” (Blaylock, 2009).

In quantum physics, the “observer effect” fundamentally changed the nature of physical models. We argue that the same holds true for cognitive models.[151] We can no longer

[151] The “Renninger negative-result experiment” is a paradoxical Gedankenexperiment posed in 1953 by the German physicist Mauritius Renninger demonstrates one of the conceptual difficulties associated with measurement and wave-function collapse in quantum mechanics. Renninger described a negative result experiment as a situation in which the detector does not detect anything. The lack of detection of a particle is still a measurement, albeit a “measurement without interaction”. Particilarly, Renninger states

unreflectively assume "cognitive realism", that is, that measurements of the cognitive system can be performed without changing the state under investigation. The implications are far reaching, both theoretically and practically. Contextual constructivism is incompatible with the notion that psychophysical and psychometric measurements objectively "read out" properties of the system under investigation. This implies *a fortiori* that the notion of a "detached" observer is no longer plausible. Every measurement (be it introspective or objective, qualitative or quantitative) needs to be regarded as an act of constructive interference. That is, the cognitive system is necessarily disturbed by any kind of measurement. The distinction between weak and strong measurements as used in quantum physics (Tamir & Cohen, 2013) should be considered in the context of psychological measurements of cognitive variables, especially in the context of psychophysics where perceptual properties can be experimentally rigorously controlled. For example, in quantum measurements, the use of an ancilla, (e.g., a current) to measure a given quantum system causes an interaction between the measurement device and the quantum system. The mere act of probing the quantum system correlates the ancilla and the system, i.e., the ancilla and the quantum system are coupled. This is congruent with the "no free lunch theorem" (Ho & Pepyne, 2002): No information can be obtained without disturbing the system under investigation. The main problem is that measurements degrade entanglement (e.g., quantum information) via decoherence. A weak measurement (weak disturbance) is associated with a weak correlation between the system and the measurement device, whereas a strong (more invasive) measurement leads to a stronger coupling between systems. Weak measurement might help to circumvent the problem of decoherence (Y.

that a particle need not be directly detected by any measurement device in order for a quantum measurement to occur (i.e., for the wave-function to collapse). Renningers argument is a refined variant of the "Mott problem" formulated in 1929 by Sir Nevill Francis Mott and Werner Heisenberg (Mott, 1929).

S. Kim, Lee, Kwon, & Kim, 2012). However, in quantum physics there is currently no universally accepted precise definition (or operationalisation) of what constitutes a weak measurement and this lack of definition obviously complicates the transfer of the concept into the psychological domain. Importantly, the kind of measurement might determine whether an object behaves classical or non-classical. As Anton Zeilinger puts it in his inaugural 2008 Newton lecture:

"*The experimenter decides whether a system is classical or quantum by choosing the apparatus, there is no objectivity … there is no border between the classical world and the quantum world, it depends on your experiment*" (Zeilinger, 2008).

Another important general question concerns what could be called "the unification problem". How does the software relate to the hardware? That is, how to the cognitive processes relate to neuronal substrates within the brain (or even the enteric nervous system)? This question is somewhat similar to the unification of chemistry and physics, or the bridging of genetics and chemistry. In this case it concerns cognition and neuroscience. Thus far, the question how quantum cognition relates to the brain (or interrelated physical/somatic substrates) has not been extensively addressed. There are some preliminary attempts, for instance, Stuart Hameroff attempts to relate quantum cognition to his Orch-OR theory (an acronym for Orchestrated objective reduction; delineated in Appendix A2) which he formulated in collaboration with Sir Roger Penrose (Hameroff & Penrose, 2014b, 2014d; Penrose & Hameroff, 2011; Penrose et al., 2011). That is, Hameroff attempts to explain quantum-like cognitive phenomena with specific quantum-dynamics at the neuronal level of dendritic-somatic microtubules which allow for topological dipole "qubits" (discussed in the associated section in the introduction) which, *ex hypothesi*, could explain quantum computations at a neuronal level. Specifically he proposes "quantum walks" (akin to Feynman's path integral) in order to account for quantum models of cognition (Hameroff, 2013, 2014). However, this is a speculative attempt without strong empirical support as the integration between quantum processes at the neuronal level and higher order quantum processes in cognition is still in its infancy stage. More empirical data is clerly needed. Nevertheless, this integral line of research might turn out to be of great pertinence for many domains of cognitive science, such as language, vision, logical reasoning, problem-solving, and creativity. Moreover, this interdisciplinary approach addresses a deep scientific question, namely, the relation between quantum-like cognitive phenomena and the brain. In other words, how do quantum processes at the cognitive level connect to neuronal processes. This important question thus addresses the unification of science and how multiple "levels of explanation" can be integrated into a holistic coherent picture which provides a more global meta-level of understanding.

6.1 Potential alternative explanatory accounts

In addition to the quantum cognition approach, there are several alternative explanatory approaches which might be contrasted in order to account for the empirical results at hand. A possible explanatory mechanism for the noncommutativity effects found in the domain of photometric contrasts might be found at the neurophysiological level, e.g., at the so called "front-end of visual phototransduction".[152] However, we maintain that the present finding cannot be parsimoniously explained in terms of specific signal transduction characteristics at the level of photoreceptor cells. For instance, one might

[152] Interestingly from both a visual science and physics point of view, when light interacts with the eye the wave-particle duality resolves, that is, observation collapses the superpositional state into a determinate eigenvalue. Einstein wrote the following on the seemingly paradoxical complementarity of physical descriptions: "*It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do*." (Einstein & Infeld, 1938, p. 278)

propose that the refractory period of the “bleach and recycle process” of phototransduction (Luo, Kefalov, & Yau, 2010) within the photoreceptive neurons of the retina might be responsible for the observed effects. That is, specific biochemical processes in opsin molecules (e.g., chromophore 11-cis retinal (P. Chen, Lee, & Fong, 2001)) might account for the observed noncommutativity effects. However, this possibility can be logically ruled out due to the bidirectional nature of the observed effects. That is, physiological mechanisms of transduction and adaptation cannot account for noncommutativity effects in visual perceptual judgment. We argue that noncommutativity is a cognitive phenomenon which is rooted in processes that are neuroanatomically localised in higher-order association cortices and therefore independent of signal transduction processes in the phototransduction cascade. However, this fundamental discussion relates to the “complementarity of psychophysics” (J. C. Baird, 1997) which conceptualises the field of psychophysics in terms of sensory (neurophysiological) versus perceptual (cognitive) processes. We are not in a position to answer this interesting question conclusively. However, we propose that the observed noncommutativity effects are caused by perceptual (cognitive) processes which cannot be reduced to cellular/molecular mechanisms (in accordance with the previously discussed principle of cognitive completeness). However, this falsifiable hypothesis should be investigated using modern neuroimaging techniques (if possible in conjunction with single-unit recordings), for instance, in the striate cortex. Such an experimental approach would potentially yield a deeper understanding of the neurophysiological basis of the processes which underlie psychophysical noncommutativity. The experiments at hand focused exclusively on the behavioural level. Hence, we cannot draw firm conclusions about the underlying neuronal mechanisms. Nevertheless, we can rule out specific theoretical accounts like receptor bleaching due to the configurational pattern of the observed effects. We propose that the visuo-spatial sketchpad (Quinn, 1988) in Baddeley's tripartite model of working memory (Baddeley, 1992, 2003) is a potential candidate for noncommutativity effects in psychological observables. However, the constructive role of physical and psychological measurements is much more complicated topic and requires a reconceptualization of sciences most basic epistemological and ontological principles, viz., naïve and local realism (as discussed earlier).

6.2 The Duhem–Quine Thesis: The underdetermination of theory by data

The sceptical reader might ask the question argue wether the data can be explained in terms of classical models. For instance, the scientific literature on perceptual contrast effects contains a multitudinous corpus of experiments and theories and we do by no means argue that there are no other explanatory frameworks (models/theories) which can *post festum* (or "*post experimentum*") account for the data at hand. In this this section we will develop an argument based on the Duhem-Quine thesis why this is necessarily the case. The following (selected) references were exclusively extracted from the literature on pertinent contrast effects in visual brightness perception (B. L. Anderson, Whitbread, & Silva, 2014; Arend, 1993; Blakeslee & McCourt, 2004; Breitmeyer, Ziegler, & Hauske, 2007; Clay Reid & Shapley, 1988; Grossberg & Todorovic, 1988; Kingdom, 2003; H. Neumann, 1996; Perna, Tosetti, Montanaro, & Morrone, 2005; Peromaa & Laurinen, 2004; Prinzmetal, Long, & Leonhardt, 2008; Purves, Williams, Nundy, & Lotto, 2004; Roe, Lu, & Hung, 2005; Schmidt et al., 2010; Shapley & Reid, 1985; Tsal, Shalev, Zakay, & Lubow, 1994; Vladusich, Lucassen, & Cornelissen, 2007).

The auditory literature on temporal perceptual context effects is presumably similarly extensive. In the visual domain, additional theories of particular pertinence for the data at hand are perceptual priming (e.g., B. P. Meier et al., 2007; Schmidt et al., 2010), perceptual anchoring effects (e.g., B. L. Anderson et al., 2014) and theories concerning temporal/sequential contrast (e.g., Eagleman, Jacobson, & Sejnowski, 2004), *inter alia*. The literature on this subset of theories is likewise extensive (for a review on "a quarter century of new ideas, captivating demonstrations and unrelenting controversy" in visual brightness perception see (Kingdom, 2011)).

Contrast effects can be classified in terms of two orthogonal perceptual carryover effects: contrast versus assimilation. Contrast occurs when the judgmenmt of the present stimulus shifts in the direction opposite to the preceeding stimuli. On the other hand, assimilation occurs when the judgment shifts in the direction of the preceding stimulus. Similarly, perceptual priming occurs when a given stimulus is enhanced/weakend by the match/mismatch between the preceding and anteceding stimuli. Moreover, within the current experimental paradigm, perceptual anchoring could be described as the process of creating (and maintaining) an association between the sensory/perceptual input and the corresponding behavioural output (in form of the selection of an appropriate spatial motor response – the rating). This process involves a symbolic reasoning component because the task requires that percept is translated into a rating on the visual analoge scale (VAS). Roughly speaking, the perceptual system has to interact with the motors system which in turn interacts with a symbol system (which executes a specific output on the VAS). The delineated procedure necessarily requires a form of symbol grounding which is explainable in terms of the general embodied cognition framework, for example, the spatial-numerical association of response codes (usually referred to as

SNARC effect) appears to be relevant in this response scenario.[153] According to theory, this "perceptual anchor" between percept and response then influences subsequent responses.

However, we would like to highlight that the three outlined theories (contrast/assimilation, perceptual priming, and perceptual anchoring) deal exclusively with the characteristics of cognitive/neuronal processes and not with the underlying Kolmogorovian statistical assumption of commutativity which the present research explicitly addresses (different levels of description). That is, along with other researchers (e.g., Atmanspacher, 2014), we specifically argue that a relaxation of the Kolmogorovian/Boolean commutativity axiom provides a novel perspective on data which are only difficult to explain within classical frameworks. The quantum cognition approach provides an overarching theoretical frame and classical frameworks can be embedded *within* its circumference. In other terms, the quantum cognition approach provides a generalised "covering law" and classical frameworks are special cases within it. This nesting of meta-theories could be visualised as a Venn diagram (Venn, 1880), see Figure 73.

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[153]The SNARC effect describes the phenomenon that people employ associations between numbers and space. For example, a by study Dehaene, Dupoux and Mehler (1990) showed that probe numbers smaller than a given reference number were responded to faster with the left hand than with the right hand and vice versa. These results indicated spatial coding of numbers on mental digit line (similar to the VAS we utilised). Relates studies indicate that associations between negative numbers and left hemiside (and contrarywise, positive numbers and right hemiside). For example, in a study by Fischer, Warlop, Hill and Fias (2004) participants had to select the larger number compared to a variable reference number of a pair of numbers ranging from –9 to 9. The results showed that negative numbers were associated with left responses and positive numbers with right responses. The mentioned results support the idea that spatial association give access to the abstract representation of modality-independent numbers (e.g., brightness ratings on a VAS).

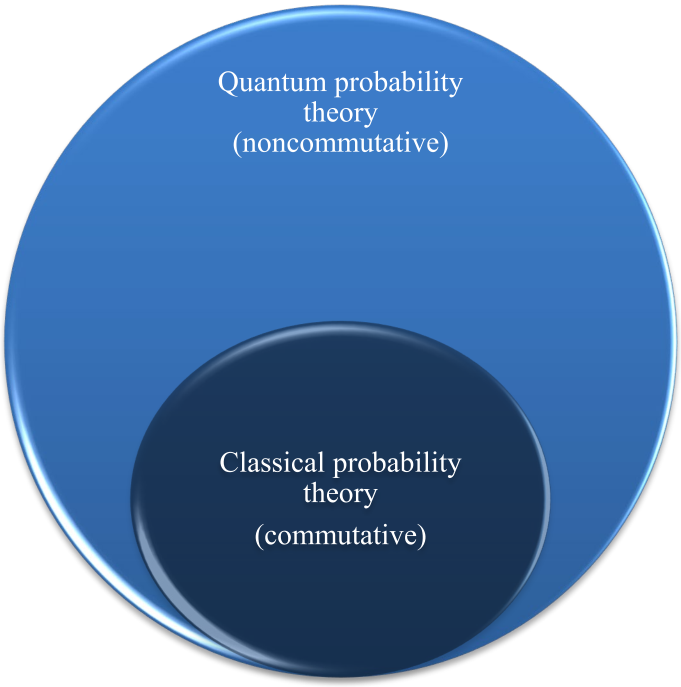

Figure 73. Classical (commutative) probability theory as special case within the more general overarching/unifying (noncommutative) quantum probability framework.

Note: *Relative proportionalities are not representative of the actual theoretical scope which remains elusive and should be empirically charted in the future.*

We are unaware of any psychophysics experiment which directly investigated photometric/audiometric contrasts in a homologous experimental design. Again, we do not argue that the quantum model is the only explanatory framework which can account for the data. However, it provides a very parsimonious account (a desideratum for every scientific theory) as it does not postulate commutativity *a priori* as other models which are based on Kolmogorovian logic do. Specifically, the vast majority of contemporary cognitive and neuroscientific models (e.g., those utilising Boolean logic or Bayes' theorem) are grounded on Kolmogorovian probability axioms which stipulate that operators obey commutativity, i.e., $P(A \cap B)=P(B \cap A)$. By contrast, quantum models are not restricted by these aprioristic structural constraints and are therefore able to parsimoniously account for numerous empirical results which appear, *prima facie*, irrational and paradoxical in the orthodox framework. Furthermore, more complex models (e.g., perceptual priming (cf. Schacter & Buckner, 1998)) make additional assumptions, i.e., they *post festum* add auxiliary hypotheses (Rowbottom, 2010) in order to be able to explain comparable datasets (specifically, they consult so called "*ad hoc* auxiliary hypotheses" (Grünbaum, 1976)). The quantum model does not make such *a priori* assumption and consequently requires fewer parameters ("sparse parametrisation"). That is, according to Occams's razor[154] (known as *lex parsimoniæ*; i.e., the problem-solving principle of parsimony of explanations), the more parsimonious model should be preferred. In other words, this widely utilised principle of reasoning is a form of an abduction heuristic (cf. Niiniluoto, 1999) which states that simplicity should be favoured over complexity. In the subsequent section titled "consilience of evidence" we develop an argument which emphasises the importance of convergence of evidence from a multiplicity and diversity of (unrelated) sources (we

[154] The principle is often stated in Latin which is helpful to precisely define its original meaning: "*Entia non sunt multiplicanda praeter necessitate*" (transl. "Entities should not be multiplied beyond necessity"). Another common expression of the principle is "*Pluralitas non est ponenda sine necessitate*" (transl. "Plurality should not be posited without necessity"). From a memetic perspective, this quasi-economical idea is not a new one and the same principle has been formulated before Occam, for instance, by Leipniz. Leipniz in turn was predated by Aristotle and it would therefore perhaps be historically more accurate to refer to the principle as "Aristotle's Razor" (as suggested by Charlesworth, 1956, in his eponymous article). In his timeless classic "Posterior Analytics" Aristotle writes: "*We may assume the superiority ceteris paribus [other things being equal] of the demonstration which derives from fewer postulates or hypotheses*" (p.150). The "*eteris paribus*" assumption (i.e., other things being equal or "held constant") is essential for the systematic design of controlled empirical scientific experiments as independent variables are usually held constant in order to be able to investigate the effect(s) of interest on the dependent variable, which (in principle) allows for the establishment of logical/statistical relations between observables (e.g., ANOVA/ANCOVA; analysis of variance/covariance). It is important to note that confounding factors can never be completely ruled out because, unbeknownst to the experimenter, a "*tertium quid*" (i.e., a third thing that is undefined but is related to two defined things) might causally interfere and confound the empirical correlation (cf. Richard Rorty, 1986). Such an unknown intervening factor might of course also be present in the current experimental context and this would of course confound our interpretation which should be regarded as a provisional "inference to the best explanation" (Ben-Menahem, 1990; G. Harman, 1992). Due to our extensive intrinsic epistemological limitation as cognising human creatures we are in no position to make absolutist truth-claims. It is crucial to reiterate that scientific knowledge is always provisional and should be revised in the light of new evidence. This reiteration is particularly important given the many self-serving biases (e.g., confirmation bias, status-quo bias, self-enhancement bias, etc. pp.) which a deep-seated in our cognitive system and which are incompatible with a truly scientific *modus operandi*.

suggest the neologism "interdisciplinary polyangualtion"). We are convinced that scientific progress requires perspectival multiplicity in order to approach a given problem. Therefore, an experiment should never be evaluated in isolation but always in a broader context of available evidence. Consquently, our results should be interpreted on the basis of the outlined empirical background and as a conceptual cross-validation (White et al., 2015, 2014b) which fits into a larger research agenda on quantum cognition (Busemeyer & Bruza, 2012).

In addition, the question of whether alternative explanatory models are "better" than the present one enters into the deep and spacious waters of philosophy of science. Model or theory comparison is never objective and straightforward. It is not simply a matter of objectively comparing various numerical goodness of fit indices for model selection with each other (e.g., χ^2, RMSEA, AIC, etc.).

It is important to note that the quasi-Darwinian scientific evaluation of model fitness always has a strong *implicit* theoretical component. Specifically, the "Duhem-Quine Thesis" (of underdetermination theory by data)[155] states that it is impossible to test a scientific hypothesis in isolation because any empirical test stipulates of one or more auxiliary hypotheses (i.e., additional background assumptions which are not part of the formal model comparison). The underdetermination argument thus states that a given piece of evidence/data is insufficient to decide which belief (a mental model or theory) one should hold. This does of course not imply that model comparison is *per se* impossible (a *non sequitur*). What this meta-theoretic reflection implies is that there are always multiple (known or unknown) theories which fit the same dataset equally well so that an objective empirical decision is an impossibility. Therefore, the phraseology

[155] A "strong version" of the collaborative thesis was later reformulated by Quine in his essay "Two Dogmas of Empiricism" (Quine, 1976). Quine's influential concept of the "web-of-belief" is of great pertinence in this respect (Quine & Ullian, 1978).

“underdetermination of theory by data”. Interpretations of experimental data should therefore always take a broader empirical perspective into account. As stated before, much of the impetus for the current investigation comes from research on noncommutativity and constructive measurement effects which reported positive results is completely different cognitive domains (White et al., 2015, 2014a, 2014b). Consequently, we provided an interpretation within a holistic empirical context. The quantum cognition approach has already been applied to a diverse body of decision-scenarios, ranging from linguistic, to probabilistic, to attitudinal, to perceptual decisions, *inter alia* (Blutner et al., 2013; Busemeyer & Bruza, 2012; Busemeyer, Wang, & Shiffrin, 2012; Kvam et al., 2015). We thus refrain from interpreting our results in isolation (a theoretical vacuum void of contextual-meaning or “empirical Gestalt”). Of course, one can evoke numerous alternative *post hoc* explanations were not part of the initial predictions, but this would be a very selective procedure and it would be prone to implicit biases (e.g., confirmation-bias (Nickerson, 1998), hindsight-bias (e.g. Hoffrage, Hertwig, & Gigerenzer, 2011)). We are aware that model comparison is often depicted as an integral part of “selling one’s research” but we think that deeper meta-theoretical reflections on the topic (and its positivistic assumptions) are at least as important as “fashionable” numerical comparisons which create the decision-theoretical impression of quantifiability and objectivity (Quine used the term “dogma of empiricism”). We think that, generally speaking, these model-comparison approaches (i.e., dichotomous either/or decisions) are oftentimes highly selective and therefore of little value to the critical reader (if not detrimental because they create the statistical “illusion of objectivity” (Berger & Berry, 1988)). Further, the Duhem-Quine thesis asserts that no single scientific hypothesis is capable of making accurate predictions. Scientific predictions usually require various auxiliary hypotheses (oftentimes implicitly) which are oftentimes taken for granted and are therefore not explicitly formulated.[156] A schematic visual representation of the Duhem-Quine Thesis is depicted in Figure 74. According to this view, an ultimately decicive *experimentum crucis* is thus epistemologically not feasible. This epistemic stance is incompatible with decisions which dichotomise model comparison. Per contrast, it is theoretically compatible with a Bayesian perspective on belief-updating which emphasises the inherently graded nature of evidence and the importance of prior beliefs which are regarded as crucial and which therefore have to be explicitly integrated in any hypothesis testing/decision procedure.

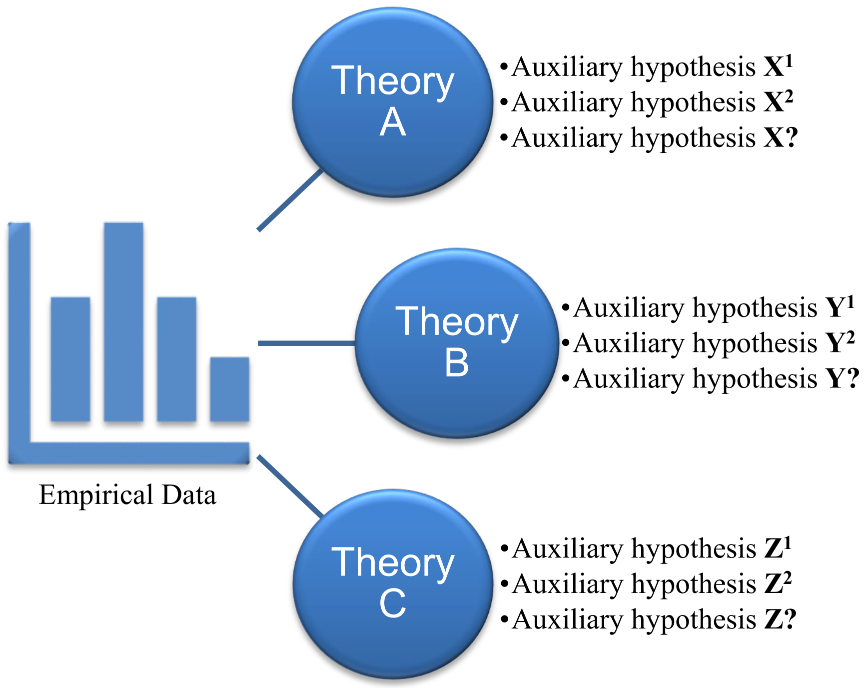

Figure 74. The Duhem-Quine Thesis: The underdetermination of theory by data.

We argue that the commutativity axiom is a paradigmatic example of an *a priori* accepted auxiliary hypothesis. In his extensive analysis of the philosophy of psychology

[156] In addition, Gödel's incompleteness theorems are relevant in context.

Wittgenstein used the term "aspect blindness" to refer to the impossibility to "see" certain phenomena which ubiquitous and therefore taken for granted. Commutativity might such a "overlooked" phenomenon because the vast majority of scientific models *prima facie* assume the validity of Kolmogorovian/Boolean logic (e.g., models in computer science, neuroscience, cognitive science, artificial intelligence, psychology, etc. pp.) The commutativity principle is implicitly assumed to be *foundational* and therefore usually escapes scientific scrutiny (in the pertinent literature this is discussed under the header "foundationalism" (Sosa, 1980)). Wittgenstein makes the following concise remark on aspect blindness:

"Who follows a rule has formed a new concept. For a new rule is a new way of seeing things" (Wittgenstein's Nachlass, 124:134–135)[159]

In other words, a theoretical release from the aprioristic constrains of the commutativity axiom might open up unforeseen novel vistas of scientific inequity. We hope that this thesis makes a small contribution to this cognitive endeavour.

6.3 Experimental limitations and potential confounding factors

In this section we will address several limitations of the experiments at hand and various potentially confounding factors. We will specifically focus on 1) sampling bias 2) the operationalization of the term "measurement" and 3) response bias and the depletion of executive resources (i.e., ego-depletion).

[159] The computerized edition entitled "Wittgenstein's Nachlass" contains Wittgenstein's complete philosophical writings and provides free access to the 20,000 facsimiles and transcriptions (Savickey, 1998). URL: http://www.wittgensteinsource.org

6.3.1 Sampling bias

The vast majority of participants was sampled from the general student population. This kind of "convenience sampling" (Etikan, 2016) can introduce potential confounds and compromises the generalisability/external validity) of the conclusions which are based on this sample. This is general problem which applies to a large segment of experimental scientific research (Bracht & Glass, 1968; C. S. Lee, Huggins, & Therriault, 2014; Rothwell, 2005; Shadish William R., 2002) because rodents and students are readily available for research. Therefore, external validity is a serious concern when one draws generic conclusions the scientific literature. The overarching questiong is: Is the sample at hand representative of the general population? This is a statistical question and various sampling strategies have been discussed for a long time, e.g., random sampling, stratified sampling, clustered sampling, adaptive sampling, systematic sampling, rational sub-grouping (e.g., Etikan, 2016; Foldvari, 1989; Imbens & Wooldridge, 2008; Sedgwick, 2014).

Given the fact that we conducted one of the experiments in India within a culturally very different population we can put forth a cogent argument which support the generalisability of our findings, specifically with respect to "cross-cultural validity" (e.g., Ember & Ember, 2009; Schwartz et al., 2001; Sekuler, McLaughlin, & Yotsumoto, 2008). Nevertheless, we sampled from a population of students which might possess certain (age-related) information processing characteristics which are not representative of the general population. Therefore, future studies should address this issue and investigate the reported effects within different age-cohorts and within non-student populations. Importantly, psychological and gerontological research indicates that perceptual mechanisms change significantly over the course of a lifetime (Comalli, 1967; Humes, Busey, Craig, & Kewley-Port, 2013). Therefore, planned comparisons between various age groups might be a fruitful research area avenue for the future.

6.3.2 Operationalization of the term "measurement"

It is crucial for every scientific experiment that all variables are clearly defined. However, the literature contains an extensive debate concerning the question what exactly constitutes a measurement. In quantum physics there is currently no universally accepted precise definition (i.e., operationalisation) of the term. However, the exact definition is of utmost importance because the operationalisation of the measurement process lies at the core of the the interpretation of quantum mechanics. However, there is currently no consensus in the scientific community and various definitions have been proposed (Penrose, Kuttner, Rosenblum, & Stapp, 2011; C. U. M. Smith, 2009; H. Stapp, 2007). From a psychological point of view, an interesting candidate is consciousness itself (Hodgson, 2012; H. P. Stapp, 2004). According to this view, a measurement always involves a conscious agent. This definition then relocates the problem: What is consciousness? We will not get into this deep philosophical question here even though it is crucial for the advancement of science as consciousness is the final frontier (one of the "open problems") and a topic of intense interest to a large number of scientists from a variety of disciplines.

This lack of a precise operationalisation in physics obviously complicates the transfer of the concept into the psychological domain of quantum cognition. Importantly, the "kind of measurement" might determine whether an object behaves classical or non-classical. For instance, it has been suggested that the decoherence problem can be circumvented by utilising weak measurements (but see Y. S. Kim et al., 2012). Anton Zeilinger addressed this point in his inaugural 2008 Newton lecture: "*The experimenter decides whether a system is classical or quantum by choosing the apparatus, there is no objectivity … there is no border between the classical world and the quantum world, it depends on your experiment*" (Zeilinger, 2008).

In the psychological experiments at hand, the measurement problem might even be more intricate than in physics because we are dealing with "introspective psychophysical measurements" which are, per definition, not objectively quantifiable. As researchers, we can only indirectly infer the underlying cognitive processes because because we lack direct access to the psychological interior of the cognisor. Therefore, future studies could employ neuroimaging techniques (e.g., EEG, fMRI, EMG, PET, NIRS) in order to obtain more “direct” quantitative readouts from the brain. These quantitative physical signals could then be correlated with the more quantitative psychological self-report data. Such a complementary analysis would provide a much broader picture of the processes under investigation. It would be particularly useful to combine imaging techniques, e.g., simultaneous EEG and fMRI, as both provide insights into different aspects of cognitive/neuronal processes. EEG has a high temporal resolution but a relatively poor spatial resolution while the opposite holds true for fMRI. Therefore, a combinatorial approach has several advantages which are discussed in greater detail by Ritter & Villringer (2006). The resulting multimodal dataset would then allow the researcher to draw joint inferences about the processes which undergird introspective measurements.[161]

6.3.3 Response bias and the depletion of executive resources (ego-depletion)

Another shortcoming of the experiments relates to the actual design. Participants had to make a large number of repetitive (monotonous) perceptual judgments. The concept of ego-depletion is thus relevant (Hagger, Wood, Stiff, & Chatzisarantis, 2010; Muraven & Baumeister, 2000). It is a well-established fact that repeated decision-making depletes executive resources (which are neuronantomically prefrontally located and which utilise a significant amount of glucose; Baddeley’s model of working memory is pertinent in this respect; but see Appendix A7). Therefore, one could argue that participants shift into an mode of responding which is “cognitively economic”. That is, after a number of repetitive trials participants might reduce their cognitive efforts and use a more unconscious/automatic *modus operandi*. In the literature on decision-making humans are described as “cognitive misers” (de Neys, Rossi, & Houdé, 2013; K. E. Stanovich, Toplak, & West, 2010). In other word, depletion of executive resources might lead to specific response biases which could confound the results in a systematic fashion.

[161] However, one should keep in mind that neuroimaging is just another form of measurment which leads arguably to a logical tautology.

Based on the available data we cannot rule out this confound and additional experiments are needed to systematically address this open question empirically. In order to investigate this hypothesis, one could conduct experiments with a varying number of trials.[162] Moreover, time-series analysis (Lund, 2007) could be utilised to statistically investigate the trajectory of perceptual judgments in a diachronic analysis (i.e., the study of change in a phenomenon over time). However, an *experimentum perfectum* is impossible as every experimental procedure comes with advantages and disadvantages. Moreover, the problem of the "*tertium quid*" (an unidentified third element which confounds the experimental results and thus their interpretation) is always lurking in the epistemological background. As researchers we can never perfectly control all variables which might play a role in an experiment, specifically because many influential factors might be completely unknown to us, hence correlation ≠ causation (under *all* circumstances). Human creatures are intrinsically very limited in their cognitive abilities (presumably because cognition was shaped by evolutionary forces which selected for survival/reproduction and not for veridical insight and propositional truths-values). Therefore, intellectual humility is crucial for the progress of science. Only if one is aware that a system is deficient is one able to develop the intrinsic motivation to improve it.

6.4 Quantum logic

Our results suggest that classical Kolmogorovian/Boolean logic might be inappropriate for models of psychophysical processes. The axiomatic basis of Bayes' theorem (which is widely applied in psychophysics (e.g., Anastasio, Patton, & Belkacem-Boussaid, 2000)) is based on the commutativity principle. Therefore, the generalizability and validity of Bayesian models needs to be questioned if psychophysical processes do not

[162] We thank Dr. Christopher Berry for providing this useful suggestion.

obey the Kolmogorovian commutativity axiom (cf. Busemeyer et al., 2011b). Quantum logic is counterintuitive and appears, *prima facie*, paradoxical and extremely irrational. To use Richard Feynman's words:

"*… I think I can safely say that nobody understands quantum mechanics. So do not take the lecture too seriously, feeling that you really have to understand in terms of some model what I am going to describe, but just relax and enjoy it. I am going to tell you what nature behaves like. If you will simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing. Do not keep saying to yourself, if you can possible avoid it, "But how can it be like that?" because you will get 'down the drain', into a blind alley from which nobody has escaped. Nobody knows how it can be like that.*" (Feynman, 1963)

However, Feynman's protective and careful advice has been questioned because he essentially argues that one should not try to understand, a statement which can be regarded as anti-rationalistic (Echenique-Robba, 2013), i.e., it is always good to think deeply about open scientific problems and the next generation of scientists should not be discouraged to do so. Based on various quasi-Piagetian considerations (e.g., Bynum, Thomas, & Weitz, 1972), we predict that future generations of scientists will be able to incorporate quantum logic more easily because they will be exposed to this kind of logic early on in their studies, whereas senior scientists have been habituated to Boolean logic since the beginning of their education (the entire developmental trajectory was overshadowed by this kind of logic). Hence, they have to overwrite the deeply engrained conditioning which makes it much more difficult to adopt the new non-Boolean logic. The adoption of a radically different logical axiomatic framework requires neuroplasticity (G. S. Smith, 2013) and synaptoplasticity (e.g., synaptic long-term potentiation in the hippocampi). Based on recent neuropsychological evidence and theorizing (Carhart-Harris, Muthukumaraswamy, et al., 2016a; Carhart-Harris & Nutt, 2017; Tagliazucchi, Carhart-Harris, Leech, Nutt, & Chialvo, 2014), we suggest that the 5-HT system (particularly the 5-HT_{2A} receptor) might play a crucial role in this context. That is, it would be interesting to investigate if changes in the structure of logical thought correlate with specific neurophysiological/neurochemical changes, for instance connectivity changes set in motion by the serotonergic neurotransmitter system (cf. Carhart-Harris et al., 2012).

Furthermore, if one agrees with the Sapir-Whorf hypothesis of linguistic relativism (Lucy, 2015; Sapir, 1929), one could argue that mathematics and logic are a kind of language and that this language influences (or in the strong version of the linguistic relativism hypothesis "determines") perception. It follows, that the logical frameworks humans are exposed to during their education, axiomatically structure (if not determine) their cognitions and perceptions in fundamental ways. Quantum logic has the potential to change our perspective on reality due to its implications for local-realism (Giustina et al., 2015; Gröblacher et al., 2007; Hensen et al., 2015). One could ask the following question: Which *Weltanschauung* emerges if metaphysical theories like local-realism and the "laws of thought" like the Aristotelian law of the excluded middle are no longer indoctrinated from an early developmental stage?" Only time will tell... In the early developmental stages neuroplasticity[163] is very high and the neural circuitry for thinking and reasoning is being formatted and structured via Hebbian processes, *inter alia*. At the same time synaptic pruning is taking place at a fast pace (Luiselli & Reed, 2011).

In our view, the multifactorial problem of understanding the paradoxical nature of quantum logic is partly due to the difficulty to represent it cognitively via somatic states

[163] That is the the growth of axons and dendrites and the formation and reorganization of synapses (Cheng, Hou, & Mattson, 2010) is much more pronounced in various "critical windows" of the developmental stages as compared to adulthood (G. S. Smith, 2013).

and simulations in the premotor cortex. That is, from a grounded and embodied cognition perspective, cognition is not computation on amodal symbols in a modular system, independent of the brain's modal systems for (e.g., vision, audition), action (e.g., movement, proprioception), and introspection (e.g., mental states, affect) (Barsalou, 2008). Instead, grounded/embodied cognition proposes that modal simulations, bodily states, and situated action underlie all of cognition. Accumulating neural evidence supports this perspective. The question thus is: What are the sensory-motor representations associated with quantum logic (such as superposition). Human beings do not experience superposition of objects during their normal development of their sensory-motor system. Hence, higher-order representations of this concept cannot be grounded in early sensory-motor experience. This lack of grounding might explain our difficulty to "grasp" these extraordinary logical concepts. In other words, we lack the primitive image schemata (Lakoff, 1987) in order to represent quantum logical concepts like superposition. Bistable visual stimuli might be the closest visual metaphor currently available to us. However, virtual reality (VR) and mixed reality (MR) (Milgram, Takemura, Utsumi, & Kishino, 1994) in combination with haptic interfaces (Hayward, Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004) could be potentially useful technological tools to enlarge our sensorimotor repertoire and to create novel percepts in order to expand our phenomenological experiences and hence our repertoire of mental representations. We propose the neologism "artificial qualia" in this context to refer to qualitative phenomenological experiences which have been specifically designed for the purpose of cognitive enhancement. If the primary axiom of embodied cognition that thought is inherently linked to sensorimotor experiences is correct, then it follows that the systematic manipulation of specific sensorimotor experiences can be utilised as a methodological tool to shape and train the intellect.[164] Aldous Huxley uses the fitting phrase "education on the nonverbal level" (Huxley, 1989) and he cites Baruch de Spinoza in this context: "Make the body capable of doing many things. This will help you to perfect the mind and come to an intellectual love of god". This resonates with the ancient science of yoga which utilises various intricate and sophisticated physical practices (Lesser, 1986) in addition to āsana (Sanskrit: आसन) in order to cultivate specific states of mind , viz., to reach a state of union (nonduality/Samādhi समाधि). *In sensu lato*, this nondual viewpoint also forms the basis of the dual-aspect monism perspective on psychophysics advocated by Gustav Fechner and modern quantum physicists like David Bohm.

From a more pragmatic/applied point of view, new models are currently being developed in various domains which utilise quantum logic principles, despite the difficulties to epistemologically appreciate quantum logic (Low, Yoder, & Chuang, 2014; Moreira & Wichert, 2016a; Tucci, 1997; Ying, 2010). For instance, "Quantum Bayesianism" in which a quantum state is utilised as "a presentation of subjective probabilities about possible results of measurements on a system" (A. Khrennikov, 2015).

6.5 The interface theory of perception

The majority of visual/perceptual scientists assume that there is a three dimensional world "out there" which contains real objects like, for instance, tigers and spiders (Hoffman, 2016). These naïve realist theorists assume that evolutionary pressures

[164] Animal and human studies indicate that the motor system (e.g., the premotor cortex) plays a central role in various cognitive functions (Rizzolatti, Fogassi, & Gallese, 2002). Moreover, the cortico-cerebellar circuit appears to be of particular importance in this respect, e.g., the symbolic representation of action (Balsters & Ramnani, 2008).

shaped and constrained our perception in such a way that it approximates veridicality. In other words, perception is assumed to provide a "true" picture of reality, albeit not a complete one (no one would argue that humans and other animals perceive reality in its entirety (inherent sensory and perceptual constrains, selective attention, sensory gating, various cognitive limitations, etc.). Perceptual interface theory challenges this notion and argues cogently that natural selection did not select for veridicality but for survival. Veridicality should not be conflated with evolutionary fitness (B. L. Anderson, 2015). That is, our perception of reality does not represent reality in its true form (the Kantian "Ding an sich", i.e.," the thing in itself" or "the thing as such"). Perception merely provides an interface which enables humans to survive. Evolution does not select for ontological truth-value but for pragmatic survival mechanisms.[165] Examples of such mechanisms are ubiquitously found in nature. Biologists and psychologists have studied so called supernormal stimuli for a long time (Lichtenstein & Sealy, 1998; Moreno, Lobato, Merino, & Mart??nez-De La Puente, 2008; Staddon, 1975). For instance, the ocean city Plymouth has a substantial European Herring Gull (*Larus argentatus*) population and these large seabirds display a salient red dot which is located on anterior part of their rather large beak (see Figure 75). Ornithologists report that the red dot on the adult seagulls beak has an important evolutionary function. It provides a visual cue for the offspring in the context of feeding behaviour. Seagull chicks are attracted by the red dot and start pecking in its presence. This simple visual cue has thus a crucial survival function in an evolutionary context. Nobel laureate[166] Nikolaas Tinbergen studied social behaviour patterns in various animals (he is regarded as the founder of ethology) and conducted insightful experiments with seagulls (Tinbergen, 1951).

[165] This has been experimentally demonstrated using Monte Carlo simulations of evolutionary games and genetic algorithms (Hoffman & Prakash, 2014).
[166] URL: https://www.nobelprize.org/nobel_prizes/medicine/laureates/1973/

Specifically, he systematically varied the properties of the adult beak and observed the effects on the behaviour of the offspring. He concluded that the reaction (pecking response) to the visual cue was innate and hence genetically coded. Tinbergen created supernormal simulacra (e.g., longer and thinner beak morphology combined with variable dot sizes) and observed that herring gull chicks pecked more frequently at seagull cardboard models with pronounced red dots as compared to the normal adult herring gull beaks (ten Cate, 2009; Tinbergen & Perdeck, 1950). That is, the offspring reacted more intense to the supernormal artificial stimuli than to the real beaks (colour was of no significant importance, what mattered was contrast and size and the form of the beak). In other words, the supernormal stimuli "hijacked" the innate instinctual response pattern ("innate releasing mechanism"). Tinbergen's student Richard Dawkins conducted similar experiments and supernormal stimuli have been found for many species including humans. For example, the multi-billion pornography industry uses supernormal visual stimuli (here it is clicking rate instead of pecking rate), as do globalised fast-food chains like McDonalds in their ubiquitous PR campaigns. The exploitation of evolutionary anchored supernormal stimuli is a ubiquitous strategy in advertising. Supernormal stimuli are systematically utilized in order to activate innate response patterns which have been "programmed" by specific natural selection pressures, i.e., the PR industry knows how "to push the right buttons".[167] Especially the dopaminergic pathways and the reward system (e.g. nucleus accumbens, ventral

[167] It could be convincingly argued that humans are as easily misled by simulacra as seagull chicks. For instance, many spend their money on attractive looking fast-food which stimulates the taste buds of the gustatory system (e.g., glutamate binding to the TAS1R1+TAS1R3 heterodimer receptors for the umami/savoury taste) instead of investing in truly nutritious food (flavour enhancers which are systematically designed by the chemical industry are supernormal stimuli). The list of supernormal stimuli in our environment specifically designed by the industry to exploit innate responses is long. One can only speculate about the epigenetics effects of such manipulations. HoweverGiven that olfactory aversion can be epigenetically imparted to the offspring (to generation F2, (Dias & Ressler, 2014)), it seems highly likely that such targeted manipulations have significant effects on gene methylation and transcription.

tegmentum) appear to be involved in the elicitation of basic biological behaviours (Salgado & Kaplitt, 2015). However, in the context of the perceptual interface theory it has been cogently argued that the chick's perceptual category "food bearer" is not a realistic representation of the true characteristics of the food-bearing parent (Hoffman, 2016). The perceptual interface of the chick does not provide a statistically accurate approximation of the real world (as argued by Bayesian models). Perception utilises a simplified (user friendly) interface which is based on superficial symbols that enable survival/reproduction, nothing more and nothing less. Because this Darwinian interface evolved over the course of millennia it has a good fitness-function in a given environmental context. However, when experimental scientist like Tinbergen enter this environment this useful interface can be dismantled and manipulated. It is important to note that the interface is generally mistaken for reality (again, the Kantian "Ding an sich"), a case of epistemological naivete. Only metacognitive processes can unveil the interface in human beings. That is, epistemology is of utmost importance in the context of analysing perception.

Figure 75. Supernormal stimuli: Seagull with a natural “normal” red dot on its beak.

The interface theory (Hoffman, 2010, 2016) thus provides a novel evolutionary perspective on perception and challenges mainstream models of perception which are based on “Bayesian decision theory and psychophysics” (Yuille & Bülthoff, 1996). These models argue that perception provides a faithful depiction of real-world properties according to specific likelihood functions, i.e., perception is based on Bayesian estimation. That is, Bayesian models of perceptions are based on the assumption that evolution selects for veridical perceptions of reality. It is assumed that neural networks implement Bayesian inference to estimate “true” properties of an objectively existing external world (Hoffman & Prakash, 2014). In John Locke’s dichotomous terminology: primary qualities[168] such as size, position, and are assumed to exist before they are perceived by an observer (R. A. Wilson, 2015). According to computational Bayesian psychophysics, perceptual biases are assumed to be caused by prior assumptions of the perceptual system. These priors are not necessarily generic but can be in competition (Yuille & Bülthoff, 1996). By contrast, according to perceptual interface theory, perception does not depict reality veridically (a naïve realist assumption) but perception provides merely a transactional (symbolic) interface (cf. the Vedantic notion of the veiling and projecting power of Māyā discussed earlier, e.g., things are not what they seem to be). According to Hoffman's theory, perception is comparable to a simplified GUI (graphical user interface), e.g., analogues to the desktop of a personal computer. An icon on the monitor might be be perceived to have a specific colour and shape and location but this does not mean that the file itself has these qualitative properties — the underlying binary computer code has no shape and colour. When a desktop icon is physically moved this virtual movement does not literally correspond to physical movement of code, there is no one-to-one correspondence between those levels description. The GUI necessarily simplifies the complexity of reality and does not represent a true state of objectively existing reality. According to Hoffman, Samuel Johnson's famous rejection of Berkley's idealism illustrates the point. Johnson kicked a stone and thought to have refuted Berkley (an invalid logical argument aginst idealism). Hofmann reasons that "*this conventionalist objection fails because it conflates taking icons seriously and taking them literally. [...] Johnson thus conflated taking a stone seriously and taking it literally. [...] Perhaps the answer lies in*

[168] Locke divides between objective primary qualities and subjective secondary properties (qualia) which are observer-dependent such as: color, sound, taste, and odor. The interface theory of perception (and numerous interpretations of quantum physics) challenge this dichotomisation and it has been argued that primary qualities are identical to secodary properties, i.e., both are observer-dependent (cf. Hacker, 1986; Priest, 1989).

the evolution of our interface. There was, naturally enough, selective pressure to take its icons seriously; those who didn't take their tiger icons seriously came to early harm. But were there selective pressures not to take its icons literally? Did reproductive advantages accrue to those of our Pleistocene ancestors who happened not to conflate the serious and the literal? Apparently not, given the widespread conflation of the two in the modern population of H. sapiens. Hence, the very evolutionary processes that endowed us with our interfaces might also have saddled us with the penchant to mistake their contents for objective reality. This mistake spawned sweeping commitments to a flat earth and a geocentric universe, and prompted the persecution of those who disagreed. Today it spawns reconstructionist theories of perception. Flat earth and geocentrism were difficult for H. sapiens to scrap; some unfortunates were tortured or burned in the process. Reconstructionism will, sans the torture, prove even more difficult to scrap; it's not just this or that percept that must be recognized as an icon, but rather perception itself that must be so recognized. The selection pressures on Pleistocene hunter-gatherers clearly didn't do the trick, but social pressures on modern H. sapiens, arising in the conduct of science, just might. " (Hoffman, 2016, p. 12)"

In addition to its relevance for perceptual psychology, we argue that Hoffman's theory is highly relevant for the classical Einstein-Tagore debate (Gosling, 2007; Home & Robinson, 1995; Sudbery, 2016) and also more generally for an understanding of Advaita Vedānta (discussed subsequently in section 6.9). Einstein and the Indian polymath Ravīndranātha Ṭhākura (Tagore) debated the nature of the relationship between mind and matter (the psychological and the physical) in a personal meeting which took place in 1930 in Berlin. Specifically, the debate between the two Nobel laureates[169] focused on nonduality, epistemology, and the fundamental ontology of reality. The crux of this dialog is also pivotal to the Einstein-Bohr debate as the following excerpt illustrates.

Einstein: "*If nobody were in the house the table would exist all the same, but this is already illegitimate from your point of view, because we cannot explain what it means, that the table is there, independently of us. Our natural point of view in regard to the existence of truth apart from humanity cannot be explained or proved, but it is a belief which nobody can lack—not even primitive beings. We attribute to truth a superhuman objectivity. It is indispensable for us—this reality which is independent of our existence and our experience and our mind—though we cannot say what it means*."

Tagore: "*In any case, if there be any truth absolutely unrelated to humanity, then for us it is absolutely non-existing.*"

Einstein: "*Then I am more religious than you are!*"

Tagore: "*My religion is in the reconciliation of the superpersonal man, the universal spirit, in my own individual being*."

Einstein reformulated his famous "I don't believe the moon only exists when I look at it" argument in the discussion with Tagore. For Tagore, on the other hand, reality is dependent on the human mind. These diametrically opposed positions seem characteristic for a detached scientist who thrives for objective, rational, and sense-independent certainty and a poet and musician who relies on intuition and subjective phenomenological experience (i.e., science vs. art, objective vs. subjective, realism vs.

[169] Einstein received his Nobel Prize in physics and Tagore in literature. Besides its cross-cultural relevance, the dialogue can therefore also be regarded as an interdisciplinary disussion between science and art.

idealism, physical vs. psychological). However, while Einstein admits that his position is a matter of quasi-religious faith, Tagore provides rational arguments to substantiate his position (Sudbery, 2016). Unfortunately, Einstein died before the violation of Bell's theorem was proven (a historical event which shed new light on the Einstein–Podolsky–Rosen paradox which is crucial to this controversy). However, a detailed discussion of the theoretical nexus of the interface theory of perception and its relation to the Einstein-Tagore debate goes beyond the scope of this thesis even though the meeting of the representatives of Western science and the Indian tradition[170] is still highly relevant today, despite the significant progress science made in the interim (also see Gosling, 2007; Home & Robinson, 1995; Sudbery, 2016). The discussion is particularly relevant in the context of psychophysics, quantum physics, and contemporary consciousness studies as it addresses the nature of the relationship between the knower and the known, the observer and the observed, the seers and the seen, psyche and physis. The main point is that cognitive psychology, evolutionary biology, and quantum physics suggest that "there is reason to disbelieve in preexisting physical truths" (Hoffman & Prakash, 2014) which are observer-independent. We will continue to discuss this dualistic theme in section 6.10. We refer the interested reader to an excellent article by Donald Hoffman in which he expounds the interface theory of perception in greater detail (Hoffman, 2016). Furthermore, a verbatim transcript of sublime discussion between Einstein and Tagore is available under the appended URL.[171] In addition, the insightful book by

[170] Einstein was already deeply impressed by the ingenuity of Indian intellectuals. For instance, Satyendra Nath Bose (the eponym of Bosons) and Einstein developed the foundations of „quantum statistics" (the succesor of Maxwell-Boltzman statistics) which are based on Bose's combinatorial formula, i.e., Bose-Einstein statistics (Germann, 2015a; Stone, 2013). We created a website entitled „quantum dice" which provides a synposis of this important chapter in the history of science:
URL: http://irrational-decisions.com/quantum_dice/
[171] Verbatim transcript of the Tagore-Einstein debate:
URL: https://www.scienceandnonduality.com/wp-content/uploads/2014/09/einstein_tagore.pdf.

Gosling (2007) discusses the cross-cultural encounter and its implications for science extensively.

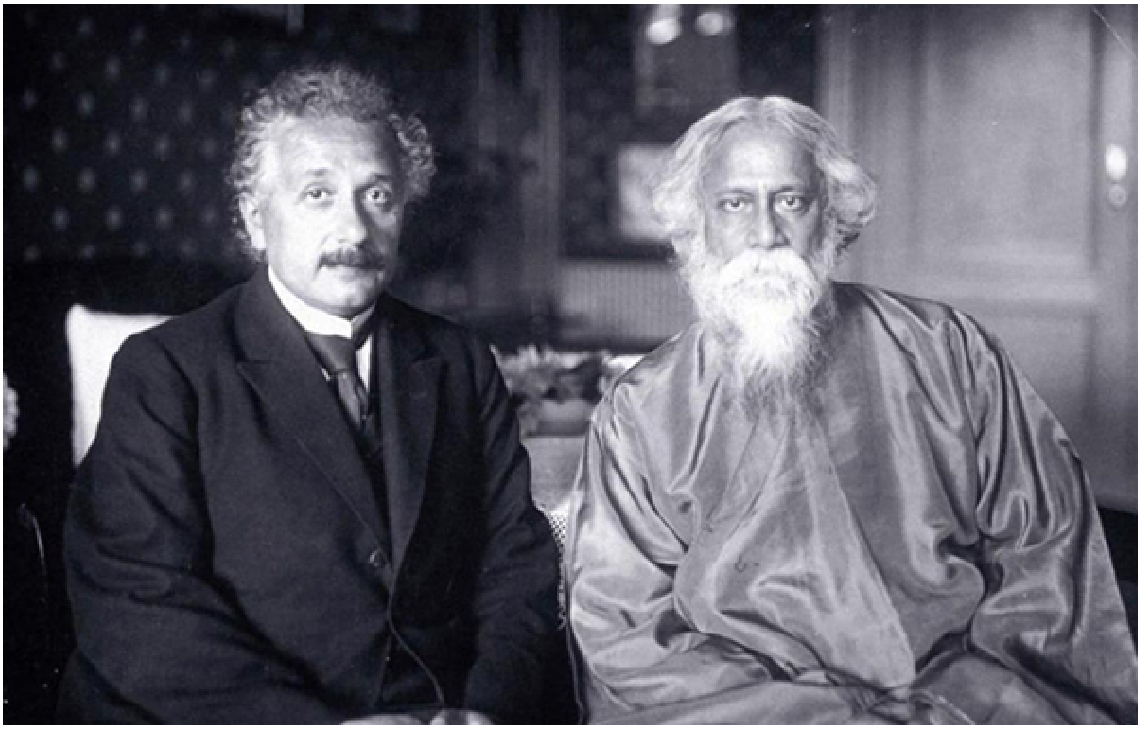

Figure 76. Photograph of Albert Einstein and Ravīndranātha Ṭhākura in Berlin, 1930 (adapted from Gosling, 2007).

6.6 The Kochen-Specker theorem and the role of the observer

The Kochen-Specker theorem (see for example Kochen & Specker, 1975) is a “no go” theorem in physics which was mathematically proved by John Bell in 1966 and by Simon Kochen and Ernst Specker in 1967. It conclusively demonstrates that it is impossible that quantum mechanical observables represent objectively observable “elements of physical reality”. More specifically, the theorem falsifies those hidden variable theories that stipulate that elements of physical reality are independent of the way in which they are measured (i.e. they are not independent of the measurement device used to measure them and are therefore inherently contextual). That is, the outcome of an experiment depends on how the experiment is designed and executed. Specifically. the theorem proves mathematically that two basic assumptions of hidden variable theories of quantum mechanics are logically inconsistent: 1) that all hidden variables corresponding to quantum mechanical observables have definite values at any given point in time 2) that the values of those variables are intrinsic and independent of the device used to measure them. The inconsistency is based on the noncommutativity of quantum mechanical observables. In colloquial language this means that the outcome of an experiments depends crucially on how we observe things. There is no outcome independent of the choice of measurement. That is, the features of the system we observe do not exist *a priori* to measuring them (Zeilinger, 2012). As Anton Zeilinger put it in an excellent interview: "*What we perceive as reality now depends on our earlier decision what to measure which is a very deep message about the nature of reality and our part in the whole universe. We are not just passive observers*" (Zeilinger, 2012). This statement connects psychology and physics (which is indicative of the deeper relevance of Gustav Fechner's "psychophysics" discussed earlier). The interdependence between the observer and the observed is known as the observer problem in quantum mechanics and its pertinence for psychology has been discussed in previous sections. In his epistemological discussions with Einstein, Niels Bohr explicitly emphasised the role of free choice on part of the observer: "...our possibility of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena we want to study" (Bohr, 1996). More recently, Rosenblum and Kuttner disagreed with Einstein when they stated that "Quantum theory thus denies the existence of a physically real world independent of its observations" (Rosenblum & Kuttner, 2011, p. 7). Einstein is known to have said that he does not believe that the moon only exists when it is observed (Germann, 2015a; Stone, 2013), a statement which epitomizes the widely held belief in an objectively existing reality. However, Einstein's ontological stance has now been conclusively experimentally falsified (e.g., Aspelmeyer & Zeilinger, 2008; Bouwmeester et al., 1997; Giustina et al., 2015; Gröblacher et al., 2007; Handsteiner et al., 2017). The deep and far reaching implications of the measurement problem cannot be simply ignored. Some physicists argue that the measurement problem is merely a "philosophical profundity" (they use the phraseology in a derogative way) and that the problem is in reality no problem. This is the "shut up and calculate" ethos advocated by a significant proportion of physicists (Kaiser, 2014; Tegmark, 2007). However, as Daniel Dennett rightly pointed out: "*There is no such thing as philosophy-free science; there is only science whose philosophical baggage is taken on board without examination.*" (Dennett, 1995). An argument which prohibits systematic thinking and the quest for understanding should concern every scientifically minded cogniser. Replies to the advice to simply ignore the foundational conceptual issues associated with the observer-problem have been articulated as follows: "Shut up and let me think!" (Echenique-Robba, 2013). It has been argued that "layers of protection against rational inquiry" have a religious undertone. For instance, Richard Dawkins criticised religion on the following grounds: "*What worries me about religion is that it teaches people to be satisfied with not understanding*." (Dawkins, 1996)

Contrast this with Feynman well known statement that nobody understands quantum physics and that one should not try — otherwise bad and scary things will happen to you!

"*On the other hand, I think I can safely say that nobody understands quantum mechanics. So do not take the lecture too seriously, feeling that you really have to* *understand in terms of some model what I am going to describe, but just relax and enjoy it. I am going to tell you what nature behaves like. If you will simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing. Do not keep saying to yourself, if you can possible avoid it, "But how can it be like that?" because you will get 'down the drain', into a blind alley from which nobody has escaped. Nobody knows how it can be like that*." (Feynman 1964)

The blind acceptance of "that just how nature is" has been adopted by generations of students. This has been compared to the "education" (i.e., operant conditioning) of children who are brought up in a traditional family and who are told by their parents to "shut up and obey" when they are still undeveloped and obedient to authority (Echenique-Robba, 2013). The anti-rationalistic argument against deeper cogitations on the interpretation of quantum mechanics takes many forms. For instance: "Don't work on this if you ever want to own a house" or "understanding is just being Newtonian" or "*whys* are the unscientific business of philosophy" (but see Echenique-Robba, 2013). We argue that psychology plays a crucial role in understanding the conceptual basis of QM and particularly the observer-effect. Further, we propose that a deeper understanding of consciousness (discussed in the subsequent section) and embodied cognition will help to clean up the "conceptual mess" (Echenique-Robba, 2013) which underpins QM. From an embodied/grounded cognition perspective, our inability to "understand" QM (e.g., concepts like superposition) might be based on a lack of appropriate sensorimotor representations which are usually acquired in early phases of development (in the Piagetian stage model sensorimotor learning and development usually takes places in a critical period which ranges from birth to about age two (Piaget, 1952)). From this perspective, the lack of somatically anchored "primary metaphors" (Lakoff, 1987, 1994; Lakoff & Núñez, 1998) which are required to represent central QM principles is responsible for our inability to “grasp” (i.e., embody) the conceptual basis of QM (currently QM is “ametaphorical”). According to the grounded cognition framework, thought is fundamentally rooted in neuronal representations associated with the perceptual and motor systems (rather than being amodal and symbolic (Barsalou, 2008)). Therefore, the systematic development of appropriate somatic representations might help humans to cognitively represent QM principles in an embodied fashion, thereby enabling a genuine understanding of seemingly paradoxical concepts via symbol grounding (cf. Gomatam, 2009). Moreover, neurogenesis, neuroplasticity, and synaptoplasticity appear to play a pivotal role in acquiring novel concepts. Therefore, certain neurochemical substances which facilitate neuroplasticity and neurogenesis are important candidates in this context. For instance, it has been shown that the nonselective 5-HT_{2A} agonist psilocybin (O-phosphoryl-4-hydroxy-N,N-dimethyltryptamine (Hofmann, Frey, Ott, Petrzilka, & Troxler, 1958; Hofmann et al., 1959)) induces neurogenesis in the hippocampus of rats, specifically in area CA1 (Catlow, Song, Paredes, Kirstein, & Sanchez-Ramos, 2013). The hippocampus crucial for various forms of learning (Manns & Squire, 2001) and learning induces long term potentiation in the hippocampus, specifically in CA1 (Whitlock, Heynen, Shuler, & Bear, 2006) which is interesting in the context of psilocybin induced neurogenesis as these regions overlap. Moreover, functional connectivity analysis using arterial spin labelling perfusion and blood-oxygen level-dependent fMRI showed that psilocybin (and potentially related tryptaminergic compounds) alters the connectivity patterns in the brain's rich-club architecture (key connector hubs) (Carhart-Harris et al., 2012). Specifically, it facilitates more global communication between brain regions which are normally disconnected, thereby enabling a state of “unconstrained cognition” which might be beneficial for a deeper understanding of complex problems (i.e., cognitive flexibility, divergent thinking, creative ideation, perspectival plurality, etc.). Interestingly, synaesthesia (Hubbard, 2007; J. Ward, 2013), i.e., cross-modal associations, can be neurochemically induced in a relatively reliable fashion. Novel cross-modal association between perceptual modalities might be very helpful for developing new insights into the persistent measurement problem in QM. Recall the Lockean associationism discussed in Chapter 1 in the context of synesthetic experiences: *Nihil est in intellectu quod non prius fuerit in sensu* (There is nothing in the intellect/understanding that was not earlier in the senses).

To highlight the importance of the measurement problem for science in general, the first Newton medal awardee Anton Zeilinger explicitly states that it is not refined to the quantum domain but it is also applicable to macro phenomena (Zeilinger, 2012). Moreover, the problem is not only relevant for physics but particularly for psychology and the neurosciences. From a (currently purely theoretical) material reductionist point of view, psychology is fully reducible to its neural substrates which in turn are composed of matter which is ultimately governed by quantum mechanical principles. Following this hierarchical (syllogistic) argument, psychology is ultimately based on quantum physics.

Considered from a broader perspective, the measurement problem is pertinent for the scientific method in general because it concerns the process of objectivity of measurements. That is, science can no longer claim detached objectivity (e.g., Pan, Bouwmeester, Daniell, Weinfurter, & Zeilinger, 2000) because experimental findings are significantly irreconcilable with the metaphysical and primarily taken-for-granted assumption of local-realism (Santos, 2016) which underlies much of contemporary scientific theorising. The measurement problem has to integrate the observer as a causal force which crucially influences the outcome of measurements. That is the observer shapes physical reality in a way which needs to be explained by physics and psychology. As we argued previously in the context of psychophysical/introspective measurements, we are not just passively recording but actively creating physical/psychological observables. In this context it has been argued that physics faces its final frontier – consciousness (H. Stapp, 2007). For instance, the "von Neumann–Wigner interpretation", also described as "consciousness causes collapse" of Ψ, postulates that consciousness is an essential factor in quantum measurements. Von Neumann uses the term "subjective perception" (J. Von Neumann, 1955) which is closely related to the complementarity of psychophysics discussed previously. In his seminal paper "Quantum theory and the role of mind in nature", Henry Stapp argues: "*From the point of view of the mathematics of quantum theory it makes no sense to treat a measuring device as intrinsically different from the collection of atomic constituents that make it up. A device is just another part of the physical universe... Moreover, the conscious thoughts of a human observer ought to be causally connected most directly and immediately to what is happening in his brain, not to what is happening out at some measuring device... Our bodies and brains thus become...parts of the quantum mechanically described physical universe. Treating the entire physical universe in this unified way provides a conceptually simple and logically coherent theoretical foundation...*"(H. P. Stapp, 2001). According to Stapp, two factors seem to be involved in any measurement: the observer (the one who is asking the question) and the observed (i.e., matter/nature). However, according to Stapp (who was a collaborator of Werner Heisenberg), quantum theory transcendents this dualistic dichotomy between epistemology and ontology because it was realized that the only "thing" that really existed is knowledge. That is, ontology is always defined by epistemology which is primary. In simple terms, knowledge (a faculty of the human mind) is primary and matter secondary (i.e., Stapp argues for "the primacy of consciousness"). In a sense, quantum physics addressed a quintessential and long-standing philosophical problem, namely how epistemology and ontology interact and interrelate to each other. Thereby, quantum physics overcomes this dualistic notion inherited from western philosophy (e.g., the Cartesian split) and merges the dualistic concepts into one integrated whole.

Following this line of thought, our beliefs about reality have to be fundamentally revised and reconceptualised. Our perspective on the relation between self and reality will never be the same. At this point it should be emphasized that physics is still in its infancy, even though it is one of the oldest and by far the most established science. Notwithstanding, current physics only deals with baryonic matter[172]. Cosmologists estimate that baryonic matter constitutes only $\approx$ 4% of the universe. The remaining 96% consist of dark matter and dark energy (Olive, 2010; Sahni, 2005). These numbers show us very clearly how limited our state of knowledge with regards to the fundamental ontology of the universe really is.[173] Psychology is a much younger than physics and therefore "epistemological humility" is a virtue which needs to be adopted by every scientist sincerely interested in the advancement of science and knowledge (a "matter"[174] of scientific integrity).

[172] A baryon is a composite subatomic particle made up of several elementary particles (i.e., three kinds of quarks).

[173] A fitting analogy can be drawn between our nescience concerning dark matter/energy in cosmology and the unconscious in psychology. These limitations might be epistemological in nature. Evolution has not equipped us humans to understand the vastness of the universe or the intricate workings of the psyche. Our neocortical structures evolved mainly to ensure survival in our immediate environment. That is, hand eye coordination, fight or flight responses, mating behaviour, etc. Questions concerning the nature of reality might just be too complex for our cognitive systems. What does an ant know about computers? With regards to consciousness a more fitting effigy might be: What does a fish know about water. That is, there are perhaps non-negotiable epistemological limitation which deterministically delimit the human gnostic horizon.

[174] From a cognitive linguistic point of view, it is interesting to note that the English language is extremely biased towards a materialistic worldview. Idioms and conceptual metaphors convey the

6.7 Consciousness and the collapse of the wave-function

In a seminal paper, Schlosshauer (2004) summarises the foundational problems modern physics faces. He focuses specifically on the adamantine "measurement problem" in quantum mechanics (cf. Ballentine, 2008; Schlosshauer, 2006; Schlosshauer & Merzbacher, 2008). This topic is to date one of the most controversial topics discussed within science. As pointed out before, particles are assumed to exist in a superpositional state (described by Schrödinger's wave-equation), i.e., particles exist as mathematical probabilistic potentialities rather than actual localisable objects. A finding which is extensively discussed in Rosenblum and Kuttner's book entitled "Quantum enigma: physics encounters consciousness" (Rosenblum & Kuttner, 2011)[175]. The key question is how particles transform from a purely mathematical probability distribution into actually existing objects as we observe them in everyday life? How is a quantum state transformed into a classical state? This is the crux of the measurement problem. In the absence of observation (measurement) particles exist in superpositional states which can only be described in mathematical terms (interestingly the tails of the distribution are, according to theory, infinitely long even though the probability of collapsing the wave-function at the outer edges becomes smaller and smaller the further one moves to the outer edges of the infinitely wide probability distribution). According to the Copenhagen interpretation of quantum mechanics, it is the act of observation which

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metaphysical ideology. For instance, the diction "it does not matter" implicitly implies that only material things are of importance. Other languages lack this specific bias (e.g., German, Dutch, Spanish). Conceptual metaphor theory is a powerful theoretical framework for the investigation of these linguistic biases which structure cognition and perception (cf. Sapir-Whorf hypothesis of linguistic relativism). According to theory, language provides a window into the underlying neuronal (sensorimotor) representations of conceptual thought. However, given that language can be classified as a System 1 process in the dual-system framework discussed earlier (at least primarily), its effects escape our conscious (extremely limited) awareness.

[175] For a critical review see (Nauenberg, 2007) and for a response (Kuttner, 2008).

collapses the presumably nonmaterial and undetermined wave-function into a determinate eigenstate /through the process of eigenselection discussed earlier). However, no exact operational definition of what defines an "observer" and an "observation" is provided within this theoretical framework. As Henry Stapp points out: *"… there is a sudden jump to a 'reduced' state which represent the new state of knowledge*" (Stapp, 1999, p.17). This "sudden jump" is a process which requires systematic scientific investigation as it concerns the interface between psychology and physics (i.e., the perennial question concerning the relationship between mind and matter). The pivotal question science struggles with is: How exactly do merely stochastic potentialities actualise? That is, how does localisable matter emerge from a purely mathematical stochastic function (Dürr, 2001)? Stapp argues that "*A superficial understanding of quantum theory might easily lead one to conclude that the entire dynamics is controlled by just the combination of the local-deterministic Schrödinger equation and the elements of quantum randomness. If that were true then our conscious experiences would again become epiphenomenal side-shows. To see beyond this superficial appearance, one must look more closely at the two roles of the observer in quantum theory*." (p.17)

Thus the missing piece in this quantum theory is a precise understanding of the mechanism responsible for the collapse of the wave-function. Schlosshauser argues that *"…without supplying an additional physical process (say, some collapse mechanism) or giving a suitable interpretation of such a superposition, it is not clear how to account, given the final composite state, for the definite pointer positions that are perceived as the result of an actual measurement— i.e., why do we seem to perceive the pointer to be in one position* $|a_n>$ *but not in a superposition of positions? This is the problem of definite outcomes.*" (p.4).

Hence, the open question can be reformulated as follows: “Why do we not observe superpositional states and how does the collapse which occurs because of a measurement actually occur? One way to collapse Ψ is through an interaction with other particles which have already taken on definite states, i.e., environmentally-induced decoherence (Anglin, Paz, & Zurek, 1997). It is possible to measure a particle with a measurement device and thereby collapse it via this interaction (collapse through interaction). To be more precise, the interaction disturbs the superpositional state of the particle. This is the decoherence effect in quantum physics and some physicist’s hypothesis that this interaction is sufficient to account for the collapse of Ψ and the measurement problem is thereby solved. However, in line with Henry Stapp, we argue that this theoretical account does not really solve the problem because it leads to an infinite regress (interestingly, this is the same problem Aristoteles described in his classic “Posterior Analytics” when he was pondering causality. Aristotle concluded that there must be an “unmoved mover” or a “final cause”, i.e., something that can cause movement but does not need to be moved by itself by another external force (viz., an “acausal causer”). In simple terms, what caused the quantum state of the particle that causes the collapse of Ψ to collapse? This chain of causal events can be continued *ad infinitum* and is therefore no real solution to the measurement problem. As Niels Bohr already pointed out, we cannot specify the wave-function of an observed particle separately from the other particle which is used to measure it. To paraphrase Bohr, the wave function of the measuring particle (e.g., the measurement device) and the particle to be measure cannot be disentangled, etc. pp., *ad infinitum*. The measuring particle inherits part of the wave-function of the particle under investigation and they become inseparably intertwined (entangled). Consequently, the particle which is measuring cannot be explained fully without taking into account what it is measuring. One needs to introduce a third particle in order to measure the measuring particle itself and the whole process repeats itself endlessly. That is, the third particle becomes entangled with the second and therefore the first particle. This logic leads to the infinite regression which lies at the core of the measurement problem. This chain of measuring particles in superposition states is called the “von Neumann chain”. From a logical point of view, there must be something which is nonlocal and outside the entire material system (cf. the Cartesian *res cogitans* vs. *res extensa*)[176] which escapes the *regressus ad infinitum*, that is, the causal chain of events – or in Aristotelian terms “the final cause” (τέλος - *teleo*s). Without such finality, efficient causality becomes tautological. This “something” (which is actually not a thing) does not obey the same physical/material laws and it is able to cause collapse within every position within the von Neumann chain. One candidate which has been proposed by several eminent physicists is human consciousness (Hagelin & Hagelin, 1981; Hodgson, 2012; Penrose et al., 2011; Rosenblum & Kuttner, 2011; H. Stapp, 2007). Taken together, this argument shows that decoherence theory which states that interaction with the environment is sufficient to solve the measurement problem is is incomplete. One needs to introduce another explanatory factor into the equation order to escape the problem of infinite regress (i.e., circular causation).

For instance, Joos (1999) states the following: “*Does decoherence solve the measurement problem? Clearly not. What decoherence tells us, is that certain objects appear classical when they are observed. But what is an observation? At some point we*

[176] Interactionist dualism (a form of substance dualism) postulates that mind and matter (psyche and physis) are two independent and inherently different substances that can bidirectionally effect each other in a causal manner (John R. Searle, 2007). It has been argued that the implicated phenomenon of “mental causation” (Esfeld, 2005, 2007) is incompatible with the physical law of conservation of energy (H. Robinson, 2016). However, others (*inter alia* Karl Popper, John Eccles, and Henry Stapp) argue that interactionism is compatible with physical law if one assumes that the mental affects the physical at the quantum (i.e., at the level of quantum indeterminacy) and that this kind of interaction might also take place at the macroscopic level (Popper & Eccles, 1977).

still have to apply the usual probability rules of quantum theory."

In the same vein Schlosshauer (2004) argues: "*let us emphasize that decoherence arises from a direct application of the quantum mechanical formalism to a description of the interaction of a physical system with its environment. By itself, decoherence is therefore neither an interpretation nor a modification of quantum mechanics*." (p.8)

The main problem is thus that the environment is subject to the same quantum laws and therefore faces the same associated problems specified above. The "final" collapse needs to be initiated by something beyond the physical system in question.

Stephen Barr (2003) describes this situation in the following terms: "*The observer is not totally describable by physics… If we could describe by the mathematics of quantum theory everything that happened in a measurement from beginning to end-that is, even up to the point where a definite outcome was obtained by the observer- then the mathematics would have to tell us what that definite outcome was. But this cannot be, for the mathematics of quantum theory will generally yield only probabilities. The actual definite result of the observation cannot emerge from the quantum calculation. And that says that something about the process of observation- and something about the observer- eludes the physical description."*

The question then becomes what differentiates the observer from the physical system under investigation. One defining characteristic is that the observer can choose between possibilities. This is known as a Heisenbergian cut, i.e., the interface between observer and observed. Everything below the Heisenbergian cut is describable by Ψ, whereas everything above is described in classical deterministic terms.

A nonconscious measuring instrument cannot achieve the collapse of Ψ. According to Henry Stapp:

“The observer in quantum theory does more than just read the recordings. He also chooses which question will be put to Nature: which aspect of nature his inquiry will probe. I call this important function of the observer ‘The Heisenberg Choice’, to contrast it with the ‘Dirac Choice’, which is the random choice on the part of Nature that Dirac emphasized.”

In a discussion with Einstein Bohr stated the following:

“*To my mind, there is no other alternative than to admit that, in this field of experience, we are dealing with individual phenomena and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena we want to study*.” (as cited in H. P. Stapp, 2004, p. 66)

The observer must first decide which aspect of a given system he intends to measure and then design a measuring apparatus in order to achieve this *a priori* specified goal.

“*In quantum theory it is the observer who both poses the question, and recognizes the answer. Without some way of specifying what the question is, the quantum rules will not work: the quantum process grinds to a halt.*” (H. P. Stapp, 1993, p. 21)

This means that only the observer has the possibility to choose between possibilities.

Davis and Gribbin argue along the same line in their book “The matter myth” that “*the observer plays a key role in deciding the outcome of the quantum measurements – the answers, depend in part on the questions asked*.” (Davies & Gribbin, 2007, p. 307)

Summa summarum, it makes no sense to deny that the observer does not play an essential role in the collapse of Schrödingers wave-function.

A recently conducted poll amonst physicist shows that the majority (55% of the sample) admits that “the observer plays a fundamental role in the application of the formalism but plays no distinguishing physical role”. Paradoxically, only 6% of the sample under investigation would agree that the observer “plays a distinguished physical role (e.g., wave-function collapse by consciousness”). This should create cognitive dissonance because the accept that the mathematics tells them that the observer plays a fundamental role but they do not accept the philosophical implications which can be deductively derived from the former statement (interestingly this is exactly the epistemological problem Einstein faced). From a purely logical point of view this makes obviously no sense at all. As Henry Stapp pointed out in his paper “Quantum theory and the role of mind in nature”, this is a “metaphysical prejudice that arose from a theory known to be fundamentally wrong”.

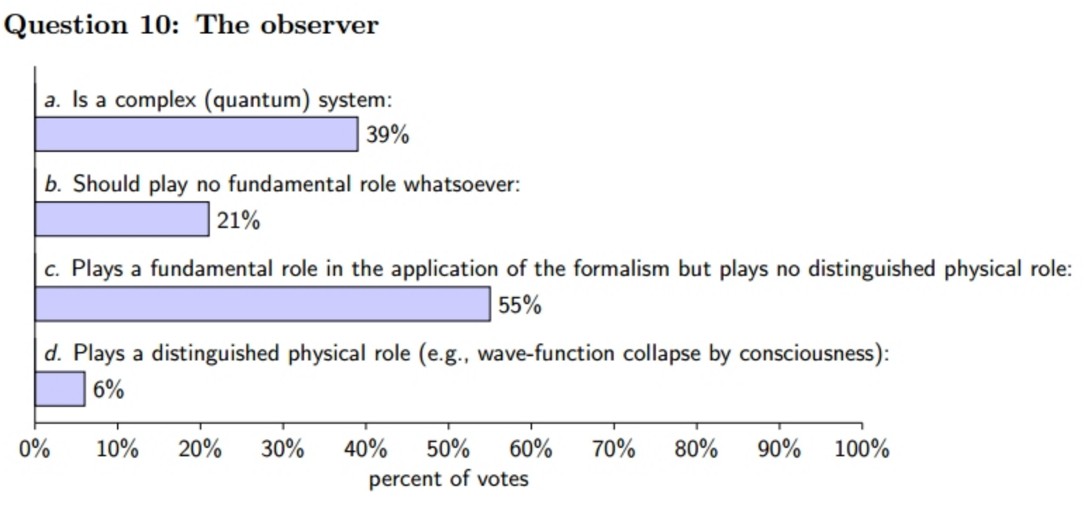

Figure 77. The attitudes of physicists concerning foundational issues of quantum mechanics (adapted from Schlosshauer, Kofler, & Zeilinger, 2013; cf. Sivasundaram & Nielsen, 2016).

In other words, even physicist who should know better implicitly (and oftentimes explicitly) hold on to unjustifiable metaphysical beliefs that quantum mechanics challenges (even in the light of clearly contradicting evidence). The superannuated materialistic Newtonian paradigm is apparently still deeply embedded in the "modi of thought" of the majority of western scientists (from a Kuhnian perspective this is not particularly surprising.

This brings the discussion back in full circle to Fechner's research agenda discussed in the introduction. How do the psyche and physis (the inner and the outer) relate to each other? Moreover, the emphasis on consciousness puts psychology at the centre of modern quantum physics. It is psychology (not physics) which has systematically studied consciousness. As science progresses, the boundaries between academic disciplines dissolve. A hitherto unanswered question concerns the perturbation of consciousness. If consciousness is involved in the collapse of Ψ, then systematic alterations of consciousness might affect the collapse. The open question is: What happens if consciousness is systematically altered? If the collapse of the wave-function depends on consciousness then it should be sensitive to alterations of consciousness. Using methods of modern physics and neuropsychopharmacology, this research question can be tested experimentally. Specifically, the 5-hydroxytryptmain (5-HT) system seems to be of significant importance due to its central role in perceptual processes and consciousness. The perceptual plasticity which is associated with 5-HT_{2A} agonism (Carhart-Harris & Nutt, 2017) is particularly interesting in this regard. Presently, systematic scientific research on naturally occurring mind-altering substances (which are endogenous to human neurochemistry) is extremely limited (even though we are currently witnessing a "psychedelic renaissance" (Bolstridge, 2013)). That is, science is systematically neglecting a specific aspect of nature. Any model which incorporates only a specific (selected) subset of the available quantitative and qualitative data is necessarily at best incomplete (and in the worst-case scenario prejudiced, dogmatic, and systematically biased). This is of pertinence for the thesis at hand because complementarity of mind and matter can only be explored if both aspects can be scientifically manipulated. Currently, matter can be manipulated (e.g., in large hadron colliders) but manipulating certain neurochemical underpinning of cognitive processes is still a taboo which is associated with a strong stigma (mainly propagated by the irrational "war on drugs" initiated under Nixon (E. Wood, Werb, Marshall, Montaner, & Kerr, 2009). Legal scholars have interpreted this situation as an attack on "cognitive liberty" (Boire, 2000; Walsh, 2016). The recently ratified UK "psychoactive substances act" which generically prohibits all mind-altering substances (besides the most harmful ones (Nutt, King, & Phillips, 2010)) makes the situation even worse. William James articulated in his classic "Essays in Radical Empiricism":

"*To be radical, an empiricist must neither admit into his constructions any element that is not directly experienced, nor exclude from them any element that is directly experienced*"

(James, 1912/1976, p.42).

However, knowledge about the knower might be in principle impossible. The question is: Can the experiencer be systematically investigated? In other words, can the observer be observed? Can consciousness investigate itself? We argue that psychedelics play an important role in this meta-cognitive (self-reflective) scientific endeavor which might turn out to be of importance for a deeper understanding of quantum physics, given the importance quantum physics places on observation and measurement (i.e., a truly psycho-physical approach in the Fechnerian sense).

As Jagadguru Śaṅkarācārya pointed out in the 8th century AD in his commentary on the Bṛhadāraṇyakopaniṣat 2.4.14 (one of the most ancient Upanishadic scriptures of Hinduism (Olivelle, 1998)):

Even in the state of ignorance, when one sees something, through what instrument should one know That owing to which all this is known? For that instrument of knowledge itself falls under the category of objects. The knower may desire to know not about itself, but about objects. As fire does not burn itself, so the self does not know itself, and the knower can have no knowledge of a thing that is not its object. Therefore through what instrument should one know the knower owing to which this universe is known, and who else should know it? And when to the knower of Brahman who has discriminated the Real from the unreal there remains only the subject, absolute and one without a second, through what instrument, O Maitreyī, should one know that Knower?

6.8 An embodied cognition perspective on quantum logic

"*The words of language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be "voluntarily" reproduced and combined. [...] The above mentioned elements are, in my case, of visual and some of muscular type.*" (Einstein quoted in Hadamard, 1996, The mathematician's mind: The psychology of invention in the mathematical field. Princeton, NJ: Princeton University Press (original work published 1945), as cited in Diezmann, C. M., & Watters, J. J. (2000). Identifying and supporting spatial intelligence in young children. Contemporary Issues in Early Childhood. 1(3), 299-313).

How do people think about things they cannot see, hear, touch, smell or taste? The ability to think and communicate about abstract domains such as emotion, morality, or mathematics is presumably uniquely human, and one of the hallmarks of human sophistication. Hitherto, the question how people represent these abstract domains mentally has not been answered definitely. Earlier classical cognitive models act on the Cartesian assumption of the disembodiment of mind (or soul, in Descartes terms). These models assume that neurological events can explain thought and related notions to the full extent. This view conforms to the computer metaphor of the mind in which thinking is solely based on brain activity or, in computer terminology, based on the central processing unit, also more commonly known as CPU (Seitz, 2000).

When the body is put back into thought (embodied cognition) a very different perspective on human thinking emerges, namely, that we are not simply inhabitants of our body; we literally use it to think. Perhaps sensory and motor representations that develop from physical interactions with the external world (i.c., vertical dimensions) are recycled to assist our thinking about abstract phenomena. This hypothesis evolved, in part, by patterns observed in language. In order to communicate about abstract things, people often utilize metaphors from more concrete perceptual domains. For example, people experiencing positive affect are said to be feeling "up" whereas people experiencing negative affect are said to be feeling "down". Cognitive linguists studying cognitive semantics (e.g., Gibbs, 1992; Glucksberg, 2001) have argued such articulations reveal that people conceptualize abstract concepts like affect metaphorically, in terms of physical reality (i.c., verticality). It has been argued that without such links, abstract concepts would lack common ground and would be difficult to convey to other people (Meier & Robinson, 2004). This approach helped scholars to draw significant links between embodied experience, abstract concepts, and conceptual metaphors.

Conceptual Metaphor Theory (Lakoff & Johnson, 1980) defines two basic roles for conceptual domains posited in conceptual metaphors: the source domain (the conceptual domain from which metaphorical expressions are drawn) and the target domain (the conceptual domain to be understood). Conceptual metaphors usually refer to an abstract concept as target and make use of concrete physical entities as their source. For example, morality is an abstract concept and when people discuss morality they recruit metaphors that tap vertical space (a concrete physical concept). In colloquial language a person who is moral is described as ‘‘high minded’’, whereas an immoral person might be denominated as ‘‘down and dirty’’ (Lakoff & Johnson, 1999). Following theory the human tendency for categorization is structured by imagistic, metaphoric, and schematizing abilities that are themselves embedded in the biological motor and perceptual infrastructure (Jackson, 1983). Supporters of this view suggest that cognition, rather than being amodal, is by nature linked to sensation and perception and consequently inherently cross-modal (e.g., Niedenthal, Barsalou, Winkielman & Krauth-Gruber, 2005). Furthermore, those researchers argue for the bodily basis of thought and its continuity beyond the infantile sensorimotor stage (e.g., Seitz, 2000). Indeed, some researchers suggest that the neurological processes that make abstract thought possible are intimately connected with the neurological processes that are responsible for representing perceptual experiences. Specifically, they argue that conceptual thought is based on sensory experience, but sensory experience is not based on conceptual thought (e.g., love is a rose, but a rose is a rose) (Meier & Robinson, 2005).

Why is an abstract concept like affect so frequently linked to concrete qualities like vertical position? One possible explanation for this perceptual-conceptual connection comes from developmental research. Early theorists of sensorimotor learning and development emphasized the importance of movement in cognitive development (e.g., Piaget, 1952). According to this perspective, human cognition develops through sensorimotor experiences. Young children in the sensorimotor stage (from birth to about age two) think and reason about things that they can see, hear, touch, smell or taste. Motor skills emerge and the infant cultivates the coordination of tactile and visual information. Later researchers postulated that thinking is an extended form of those skilled behaviours and that it is based on these earlier modes of adaptation to the physical environment (Bartlett, 1958). For example, it has been suggested that gesture and speech form parallel systems (McNeill, 1992) and that the body is central to mathematical comprehension (Lakoff & Nunez, 1997).

When children get older they develop the skills to think in abstract terms. These skills maybe built upon earlier sensorimotor representations. For example, a warm bath leads to a pleasant sensory experience and positive affect. In adulthood, this pairing of sensory and abstract representations may give rise to a physical metaphor (e.g., a warm person is a pleasant person) that continues to exert effects on representation and evaluation (Meier & Robinson, 2004). Transferred to the vertical representation of affect one can only speculate. Tolaas (1991) proposes that infants spend much of their time lying on their back. Rewarding stimuli like food and affection arrive from a high vertical position. The caregiver frequently appears in the infant's upper visual-spatial environment (Meier, Sellbom & Wygant, 2007). As children age, they use this sensorimotor foundation to develop abstract thought, as recognized by developmental psychologists (e.g., Piaget & Inhelder, 1969). This early conditioning leads adults to use the vertical dimension when expressing and representing affect. These considerations suggest that the link between affect and vertical position may develop early in the sensorimotor stage (see Gibbs, 2006; for sophisticated considerations).

From theory to experimental applications

Affective metaphors and related associations apply to a multitude of perceptual dimensions such as, for example, spatial location, brightness and tone pitch. A plethora of studies investigated the link between abstract concepts (i.c., affect) and physical representation (i.c., verticality). For example, in a study by Meier and Robinson (2004) participants had to evaluate positive and negative words either above or below a central cue. Evaluations of negative words were faster when words were in the down rather than the up position, whereas evaluations of positive words were faster when words were in the up rather than the down position. In a second study, using a sequential priming paradigm, they showed that evaluations activate spatial attention. Positive word evaluations reduced reaction times for stimuli presented in higher areas of visual space, whereas negative word evaluations reduced reaction times for stimuli presented in lower areas of visual space. A third study revealed that spatial positions do not activate evaluations (e.g., “down” does not activate ‘‘bad’’). Their studies give credit to the assumption that affect has a physical basis.

Moreover, an often cited study by Wapner, Werner, and Krus (1957)examined the effects of success and failure on verticality related judgements. They found that positive mood states, compared to negative mood states, were associated with line bisections that were higher within vertical space.

In a recent study Meier, Hauser, Robinson, Friesen and Schjeldahl (2007)reported that people have implicit associations between God-Devil and up-down. Their experiments showed that people encode God-related concepts faster if presented in a high (vs. low) vertical position. Moreover, they found that people estimated strangers as more likely to believe in God when their images appeared in a high versus low vertical position.

Another study by Meier and Robinson (2006) correlated individual differences in emotional experience (neuroticism and depression) with reaction times with regard to high (vs. low) spatial probes. The higher the neuroticism or depression of participants, the faster they responded to lower (in contrast to higher) spatial probes. Their results indicate that negative affect influences covert attention in a direction that favours lower regions of visual space. In second experiment the researchers differentiated between neuroticism and depression. They argued that neuroticism is more trait-like in nature than depression (which is more state-like). The researchers concluded from their analysis that depressive symptoms were a stronger predictor of metaphor consistent vertical selective attention than neuroticism.

Similar results emerged when dominance-submission was assessed as an individual difference variable and a covert spatial attention tasks was used to assess biases in vertical selective attention (Robinson, Zabelina, Ode & Moeller, in press). Linking higher levels of dominance to higher levels of perceptual verticality they found that dominant individuals were faster to respond to higher spatial stimuli, whereas submissive individuals were faster to respond to lower spatial stimuli.

Further support for the Conceptual Metaphor Theory comes from a study investing the extent to which verticality is used when encoding moral concepts (Meier, Sellbom & Wygant, 2007). Using a modified IAT1 the researchers showed that people use vertical dimensions when processing moral-related concepts and that psychopathy moderates this effect.

As mentioned above, affective metaphors and related associations apply multitudinous perceptual dimensions. Recent research examined the association between stimulus brightness and affect (Meier, Robinson & Clore, 2004). The investigators hypothecated that people automatically infer that bright things are good, whereas dark things are bad (e.g., light of my life, dark times). The researchers found that categorization was inhibited when there was a mismatch between stimulus brightness (white vs. black font) and word valence (positive vs. negative). Negative words were evaluated faster and more accurately when presented in a black font, whereas positive words were evaluated faster and more accurately when presented in a white font.

Furthermore, a series of studies showed that positive word evaluations biased subsequent tone judgment in the direction of high-pitch tones, whereas participants evaluated the same tone as lower in pitch when they evaluated negative words before(Weger, Meier, Robinson & Inhoff, 2007) .

Moreover, cognitive psychologists have shown that people employ association between numbers and space. For example, a by study Dehaene, Dupoux and Mehler (1990) showed that probe numbers smaller than a given reference number were responded to faster with the left hand than with the right hand and vice versa. These results indicated spatial coding of numbers on mental digit line. Dehaene, Bossini and Giraux (1993) termed the mentioned association of numbers with spatial left-right response coordinates the SNARC-effect (Spatial-Numerical Association of Response Codes). Another SNARC-effect related issue is that empirical data indicates that associations between negative numbers with left space exist. For example, in a study by Fischer, Warlop, Hill and Fias (2004) participants had to select the larger number c to 9. The results showed that negative numbers were associated with left responses and positive numbers with right responses. The mentioned results support the idea that spatial association give access to the abstract representation of numbers. As mentioned above, mathematicians like Einstein explicitly accentuate the role of the concrete spatial representation of numbers for the development of their mathematical ideas. Today there are a few savants which can do calculation up to 100 decimal places. They also emphasize visuo-spatial imagery as in the case of Daniel Tammet who has an extraordinary form of synaesthesia which enables him to visualize numbers in a landscape and to solve huge calculations in the head. Moreover, about 15% of ordinary adults report some form of visuo-spatial representation of numbers (Seron, Pesenti, Noel, Deloche & Cornet, 1992).

However, the quantum mechanical concept of superposition transcends the dualistic representation which form the basis of so many conceptual metaphors by negating the third Aristotelian law of the excluded middle, the *tertium non datur* (lit. no third [possibility] is given) a.k.a. *principium tertii exclusi*. This "law of thought" stipulates that any given proposition can either be true or false (there is no middle ground in-between). It implies that either a proposition is true, or its negation is true.

From a cognitive linguistics point of view, concepts like morality and affect are anchored in spatial representations. These are called primary metaphors, other examples include vertical metaphors like "up is more" or emotional/sensory metaphors like "affection is warmth"[177], or perceptual metaphors like "good is bright" etc. These concepts are not superimposed but mentally represented as opposites (in vertical and/or horizontal space).

On the basis of psychological and empirical evidence, it can be convincingly argued that mathematical concepts are inherently rooted in sensorimotor representation (Lakoff & Nuñez, 2000). Our perception of space is restricted to three dimensions. However, multidimensional Hilbert space is not grounded in our embodied neural/sensorimotor representations of mathematical concepts. Our logical inferences are based on metaphors, we take inferences from a source domain and apply them to a target domain,

[177] From an embodied cognition perspective, warmth is associated with early experiences of affection during the sensorimotor stage of development. Interestingly, the insular is involved in the underlying neuronal ciruit, and it is this neuronal circuitry which form the basis of the conceptual metaphor. The question why "affection is warmth" and "warmth is not affection" can be answered as follows: The primary metaphor is always the more fundamental. Thermoregulation via the hypothalamus is an ongoing process, i.e., our brain constantly computes temperature whereas the activation of affective states is something which happens only infrequently. Therefore, temperature forms the source domain and affect the target domain in the construction of the metaphor (Lakoff, 1993). The directionality of the metaphor is thus determined by its neuronal underpinnings.

e.g., “happy is bright” and “sad is dark”, or “up is good” and “bad is down” (Barsalou, 2008; Lakoff, 1987, 1993; Lakoff & Johnson, 1980). According to theory, the same somatic mappings underlie the cognitive foundations of logic and mathematics (Lakoff & Johnson, 1980; Lakoff & Nuñez, 2000). From this perspective our understanding of quantum logic must thus be grounded in sensorimotor representations, how else would one cognitively represent abstract thought? From an embodied cognition point of view, the notion of disembodied thinking (purely “platonic” computation) has been clearly rejected. Any form of cognition is always grounded in sensorimotor representations (Lakoff & Nuñez, 2000). However, many mathematicians implicitly subscribe to a Platonic view on abstract mathematical reality which is a disembodied form of mathematics. From a grounded cognition perspective, modal simulations of bodily states underlie cognition and hence mathematical and logical reasoning (Barsalou, 2008). It follows that mathematics is not detached and dissociated from the genetic and neuronal predispositions which underlie human cognition, as the Platonic “abstract universal mathematics” perspective would hold. The questions has been posed before as follows: “*… is there, as Platonists have suggested, a disembodied mathematics transcending all bodies and minds and structuring the universe-this universe and every possible universe?*” (Lakoff & Nuñez, 2000, p. 1) However, the question of how to cognitively represent superpositional states in multidimensional Hilbert spaces remains still an open one. And what role does embodied cognition play in this context or is quantum logic independent of physical representations as Platonists would believe? Conversely, we propose that the concept of superposition might be especially relevant for cognitive representations of concepts, specifically in the context of integrating multiple “binding circuits” (Lakoff, 2014). According to theory, the entire system is based on these perceptual primitives which are binary in nature (warmth vs. cold, up vs.

down). The concept of superposition transcends the dichotomies which are intrinsic to these schemas. A visual metaphor superposition is provided bistable visual stimuli like the Rubin's Vase (Pind, 2014) discussed in the introductory chapter. Those ambiguous visual stimuli seem to convey much deeper epistemological information about the psychophysical nature of perception (Atmanspacher, 2002; Atmanspacher & Filk, 2010). According to theory (Lakoff, 1993; Lakoff & Nuñez, 2000), abstract thought is based on the combination of complex metaphors. We suggest that superposition (e.g., bistable perception) is a perceptual schema in itself and it follows its own logic which sets it apart from classical visual metaphors (e.g., the spatial logic of containment which underlies set theoretical reasoning processes). An interesting question is whether other cultures have metaphors for superposition. We already discussed Bohr and the Yin & Yang symbol before. For an article on "the role of metaphor in information visualization" see (Risch, 2008). The role of neuro-cognitive linguistics is to make the unconscious embodied architecture of cognition visible. Given that most of cognition occurs at an unconscious level, cognitive linguistics has to deal with mainly unconscious concepts and frames (and how these are embodied from a neuronal point of view).

6.9 Advaita Vedānta, the art and science of yoga, introspection, and the hard problem of consciousness

The great ancient knowledge system of India known as Vedānta has several schools of thought and forms the rational philosophical system which is the foundation of Hinduism. It is based on various Upanishads[178], the Brahma Sūtras, and the Bhagavad Gītā. It provides a profound science[179] of the mind and consciousness which is relevant for contemporary westerns sciences like psychology, neuroscience, biology, and physics (Frawley, 2001; Silberstein, 2017; Vaidya & Bilimoria, 2015). Most Vedāntic schools of thought are dualistic in nature with the exception of Advaita Vedānta which is furthermore incompatible with superficial and naïve materialistic ideologies (e.g., naïve realism). Its introspective methods permit deep insights into the nature of the self (via systematic meditation and self-reflection) which are pivotal for the understanding of the nature of mind and consciousness which lies at the very heart of all sciences because ultimately all knowledge is in the mind (i.e., the primary instrument of science is the mind). Especially, the non-dualistic school of Advaita Vedānta is pertinent in the current context. Advaita (Sanskrit[180]: अद्वैत वेदान्त is also known as Puruṣavāda) literally means "not-two" (a = not, dvaita = two).[181] Advaita Vedānta is not a beliefsystem but it

[178] The Upanishads are the portion of the Vedas (Veda वेद meaning knowledge) which primarily deals with knowledge of the self. Many core principles of the Upanishads are shared with Buddhism.
[179] The Advaita Vedānta terminology might easily put off those with a certain Western analytic bias (i.e., those who are biased and prejudiced towards materialism), as has been pointed out by Silbestein (2017, p. 1139). However, we urge those readers to supress their (enteric) gut-reaction and aknowledge the antiquity and pertinence of this school of thought for the contemporary debate of consciousness and psychophysics. Hence our entreaty for nondogmatism and openmindendness formulated in the introduction of this thesis.
[180] Sanskrit does not only refer to a language but to an ancient culture with a prehistory of more than 5000 years and it spread across a vast territory of Asia over a period of circa 2000 years (Bhate, 2010).
[181] While the English language is very capable of describing material aspect of reality Sanskrit has a vast vocabulary for psychological processes, a fact which is interesting from acognitive linguistics perspective (i.e., linguistic relativism a la Sapir-Whorf (Sapir, 1929)).

is based on first-person phenomenological experiences which have been cross-validated countless times over many millennia and in different cultural contexts. Yoga, prāṇāyāma, philosophical inquiry, introscpective psychological analysis, a Sattvic vegetarian diet, meditation, purity in intention/thought/word/action, etc. are tools utilised to systematically purify and prepare body and mind in order to facilitate the experience of nondual consciousness, i.e., various forms of Samādhi (समाधि), e.g., Savikalpa Samādhi (meditation with support of an object, I-am-ness), and ultimately Nirvikalpa Samādhi (nonconceptual pure awareness, complete absorption without self-consciousness). Recently, specific EEG (Electroencephalography) frequency band characteristics have been proposed in "an attempt to create taxonomies based on the constructs of contemporary cognitive sciences" (Josipovic, 2010, p. 1119). Moreover, an excellent article entitled "Neural correlates of nondual awareness in meditation" has been published in the "Annals of the New York Academy of Sciences" and discusses data which indicates the involvement of a precuneus[182] network in nondual awareness (Josipovic, 2014). Josipovic gives the following preliminary definition: "*Dualities such as self versus other, good versus bad, and in-group versus out-group are pervasive features of human experience, structuring the majority of cognitive and affective processes. Yet, an entirely different way of experiencing, one in which such dualities are*

[182] The precuneus is „the functional core of the default-mode network" (Utevsky, Smith, & Huettel, 2014) which is activated when an individual is not focused on the external physical world (i.e., extrospection). The precuneus is part of the superior parietal lobule which is anatomically located anterior of the occipital lobe. Interestingly, a recent fMRI study demonstrated a drecrease in functional connectivity within the precuneus after Ayahuasca intake (Palhano-Fontes et al., 2015). Ayahuasca is a phytochemical concoction which has been used by indegenous people in the Amazonian rainforests for unknown times. It combines N,N-Dimethyltryptamine (DMT, which is structurally very closely related to serotonin) with a monoamine oxidse inhibitor to prevent th enzymatic breakdonw of DMT within the gastro-intestinal tract. Ayahusaca (and DMT in its pure chrystaline form) can occasion nondual experiences (but see 0 and 0). Based on the concgruence of these unconected empirical findings we propose the experimentally testable hypothesis that nondual states induced by serotonergic psychedelics (especially 5-HT_{2A} agonsists) and those faciliatted by various mediatation techniques share similar underlying neural correlates. Such a convergence would establish the common neural basis of nondual awarenss induced by completly difefrent methods which evolved in different socio-cultural contexts.

relaxed rather than fortified, is also available. It depends on recognizing, within the stream of our consciousness, the nondual awareness (NDA)--a background awareness that precedes conceptualization and intention and that can contextualize various perceptual, affective, or cognitive contents without fragmenting the field of experience into habitual dualities." (Josipovic, 2014, p. 9)

Because most of westerns psychology is caught up in externalities due to the constant focus on an external locus of stimulation and sensation it is predominantly concerned with the limited personal self (the transactional self) in addition to various unconscious processes.[183] Vedānta places great emphasis on introspection, contemplation, and meditation. In "the western world", the majority of psychologists have never engaged in systematic introspective mediation (Siegel, 2010) and are therefore unfortunately utterly unaware of the workings of their own mind (a defining characteristic of contemporary Western materialistic consumer societies). In a neuropsychological context the composite lexeme "mindsight" has been proposed to describe this discerning metacognitive process (Siegel, 2009, 2010). Currently, introspection is not part of the academic psychology curriculum even though it is indispensable for a genuine science of the mind (and beyond). Therefore, the vast majority of psychologists lack

[183] Freudian psychoanalysis mainly focuses on the unconscious aspects of the mind (the mind is not identical to consciousness – this crucial distinction is often confused) but Freud was unaware of the higher aspects of universal consciousness and self-realisation. The mind is thus mainly defined in social and physical terms. Jung extended the Freudian model and focused on the collective unconscious and its archetypal contents. However, both are currently not accepted in mainstream academic discourse, i.e., their complex theories are not part of the majority of psychology curricula and are often superficially dismissed as pseudoscience (Popper, 1959, 1962).

phenomenological access to the experience of unity consciousness[184], an experiential phenomenon which has been documented across cultures and epochs (James 1842-1910, 1902). Due to a lack of phenomenological access, psychologists might even disregard transcendental states as mere phantasms or chimera. It can be cogently argued that psychologists (and scientists in general) should be trained in these self-reflective experiential techniques in order to better understand the workings of their own mind which would not only benefit their general mental health and well-being but would also enable them to explicitly address all kinds of irrational cognitive biases, motivations, desires, and delusions which would be extremely beneficial for the progress of science in general. Otherwise psychologists lack the most basic cognitive tools and will not understand[185] their own mind and consciousness and will be in no position to appreciate the timeless profound contemplative traditions of many cultures. That is, nondogmatic (secular) meditation practices should be integrated into the psychology curriculum – in the same way personal psychoanalysis was crucial in the education of psychoanalysts in the last century for psychologists. We could provide extensive arguments for this recommendation, but we will abstain from doing so for reasons of parsimony and focus

[184] Charles Tart pointed out in his SCIENCE article "States of Consciousness and State-Specific Sciences" that altered states of consciousness (ASCs) resemble a Kuhnian paradigm: "The conflict now existing between those who have experienced certain ASC's (whose ranks include many young scientists) and those who have not is very much a paradigmatic conflict […] A recognition of the unreality of the detached observer in the psychological sciences is becoming widespread, under the topics of experimenter bias (8) and demand characteristics (9). A similar recognition long ago occurred in physics when it was realized that the observed was altered by the process of observation at subatomic levels. When we deal with ASC's where the observer is the experiencer of the ASC, this factor is of paramount importance." (Tart, 1972, p. 1205) However, the term "altered states of consciousness" is not the best choice because it can be persuasively argued that consciousness is unchangeable, what changes is the mind. Therefore, a better term would be "altered states of mind".

[185] The analogy of a neurologist who has never seen a brain lags behind because neuroanatomical knowledge can in principle be acquired through other sources of knowledge (e.g., books, lectures, videos, computer simulations, etc.) The symbol grounding problem as illustrated by John Searle in his "Chinese room argument" is perhaps more appropriate because what is lacking is understanding or first-hand experiential grounding (J. R. Searle, 1982). This relates to Aldous Huxley's criticism of the purely abstract and symbolic nature of education (Huxley, 1989) which neglects psychosomatic and phenomenological aspects. We will come back to this point in the context of recent empirical findings in the field of embodied (Lakoff, 1987) and grounded cognition (Barsalou, 2008).

and refer to Daniel Siegel's book "Mindsight: The New Science of Personal Transformation" (Siegel, 2010) for an extensive discussion of the topic.[186]

Yoga and Vedānta emphasise the unity between the individual self (Brahman) and the universal supreme consciousness (Ātman/Jivātman /Purusha) which is thought to be manifested in all forms of life (the universal reality behind all of apparent existence). In other words, the manifestation of consciousness within each of us and the consciousness which pervades the entire universe is identical and hence singular, a perspective which recently received much attention in the context of consciousness studies (Bayne & Chalmers, 2012; D Chalmers, 2015, 2016; Vaidya & Bilimoria, 2015). Advaita Vedānta is a sophisticated philosophy that demands self-examination and self-reflection (via yogic practices like asana[187] and mediation[188]), that is, the contents of the mind and the

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[186] Abraham Maslow argues in his book "The Psychology of Science" that "there is no substitute for experience, none at all. All the other paraphernalia of communication and of knowledge – words, labels, concepts, symbols, theories, formulas, sciences — all are useful only because people already know experientially. Interestingly, he refers to Niels Bohr and the complementarity principle in this context: "This world of experience can be described with two languages, a subjective, phenomenological one and an objective, "naïvely realistic" one, as Niels Bohr pointed out long ago. Each one can be close to the language of everyday life, and yet neither describes life completely. Each has its uses and both are necessary." (Maslow, 1962, p. 29)

[187] The physical practice of asana आसन is particularly interesting from an embodied cognition point of view. Embodied cognition (Lakoff, 2014) and grounded cognition (Barsalou, 2008) argue for the bodily basis of thought. That is, abstract thought is inherently cross-modal and rooted in the sensorimotor systems of the brain (rather than being amodal and purely symbolic). Therefore, asana can be viewed as a systematic enlargement of the sensorimotor repertoire, thereby providing the neural basis for novel forms of abstract thought. Following this argumentative line, asana can thus be regarded as a technique for cognitive development. Aldous Huxley provided the following remarkable quote by Baruch de Spinoza (who can be regarded as a dual-aspect monists): "Teach the body to become capable of many things. In this way you will perfect the mind and permit it to come to the intellectual love of God." Huxley present this quote in his lecture "Realizing human potentials" (Huxley, 1989) as part of his important argument that education places too much emphasis on symbolic (e.g., verbal/mathematical) activity while it neglect the intimate relation between body and mind. This is now empirically supported by a vast array of neuroscientific and psychological studies which were conducted in the framework of embodied cognition which is also of great importance for the field of AI (but see M. Anderson, 2003). The non-dual science/art of yoga, on the other hand, always placed great importance on the integrative relationship between mind and body (cf. the perennial mind-body problem (Blanke & Thut, 2012; Damasio, 2000; Daniels, 1976; Feyerabend, 1963; Fodor, 1981; Hoffman, 2008; Wimsatt, 1976)).

[188] The Sanskrit term is dhyāna ध्यान, and it can be translated as "to think, to contemplate, to ponder" even though the penultimate goal of meditation is to transcend conceptual though i.e., Nirvikalpa samādhi, a non-conceptual state of absorption without self-awareness in which the dichotomy between the observer and the observed (the seer and the seen) dissolves. The contemporary analogue in psychology and neuroscience might be "ego-dissolution" (Millière, 2017). Interestingly, cutting-edge neuroscientific evidence (using various sophisticated neuroimaging techniques like fMRI and arterial spin labelling)

ego construct are carefully investigated in a scientific and rational manner leading to self-knowledge (atma jñāna[189]) and self-realisation (cf. Maslow, 1968). The famous "*Tat Tvam Asi*" (Thou art that) is one of the Mahāvākyas (grand pronouncements) of Vedāntic Sanātana Dharma (eternal laws). It originated from the Chandogya Upanishad, one of the oldest Upanishads which is estimated to be composed in the early 1st millennium BCE (Olivelle, 1998). In Buddhism (which is an offshoot of Hinduism), jñāna refers to pure (conceptual) awareness. In the spiritual practice of Advaita Vedānta, mental contents are subjected to systematic introspective observation. This leads to a dissociation (detachment) from the contents of thought (the observer is independent from the contents of the mind – as exemplified by the mantra (मन्त्र) "I am not the body, I am not the mind)" which is used to induce an altered state of consciousness (yoga[190]) (cf. Tart, 1972, 2008). This intense metacognitive activity fosters a deeper understanding of self and the relation between the self and the universe. The silencing of the mind can occasion a profoundly transformative unity experience (Samādhi) which unifies the individual consciousness with the universal consciousness. This intellectual heritage of India is very important for contemporary western science and it needs to be integrated into our knowledge system (a truly interdisciplinary and cross-

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indicates that ego-dissolution can be occasioned by certain naturally occurring (and sometimes endogenous) neurotransmitter like substances which bind primarily to the 5-HT_{2A} receptor subtype (Carhart-Harris, Muthukumaraswamy, et al., 2016b; Lebedev et al., 2015; Nour et al., 2016a). For the first time in the history of humanity, science is thus in a position to experimentally induce non-dual states of consciousness in a repeatable and rigorously controlled fashion. These neurochemical tools (especially the tryptaminergic psychedelics) are therefore of great importance for our understanding of psychophysics and consciousness in general. The more general importance of this paradigm-shift in consciousness will be discussed subsequently.

[189] The root of the Sanskrit term jñāna (ज्ञान) which is pronounced as /dʒəˈnɑː.nə/ (IPA, International Phonetic Association, 1999) is an etymological cognate to the English term "knowledge", as well as to the Greek γνώ (as in gnosis γνῶσις).

[190] Yoga योगः literally means "to join" or "to unite" and it forms the basis for the English term union/unity. In Vedānta, the term yoga implies the union between Atman and Brahman (i.e., the individual self unites with universal consciousness – a profound and transformative non-dual experience which has been described in many cross-cultural contexts (Bayne & Chalmers, 2012; Elder, 1980; James 1842-1910, 1902; Raymont & Brook, 2009).

cultural endeavour). Besides its significant theoretical contributions to the corpus of human knowledge, this complex knowledge system has far reaching moral and ethical implications (Nirban, 2018) due to the emphasis of the unity of all living beings[191] - a holistic/organismic perspective which is antagonistic with the individualism of western societies (Hofstede, 2001).

"*The goal of Advaita Vedānta is to show the ultimate non-reality of all distinctions; reality is not constituted of parts*." (Gupta, 1998, p. 1)

Advaita Vedānta is relevant in the context of "the hard problem of consciousness" (D. J. Chalmers, 1995; David Chalmers, 2007; John R. Searle, 1998; C. U. M. Smith, 2009). Neuroscience is currently unable to account for consciousness and "the generation problem of consciousness" looms large[192]. At the same time the role of observation is an unsolved puzzle in quantum physics. There appears to be some convergence between neuroscience, psychology, and physics on the topic of consciousness. However, science is currently not in a position to articulate what this convergence exactly entails. The relationship between the observer and the observed seems to play a central role in this

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[191] For instance, the cardinal virtue ahiṃsā अहिंसा (nonviolence, or more specifically, harmlessness) is integral the Vedantic tradition. Historically, our respect for animals increased over time. For instance, Descartes believed that animals are merely machines and that only humans possess a soul. We argue that our respect for other living creatures grows diachronically in proportion to the evolution of human consciousness. To quote the great author Leo Tolstoy: "*As long as there are slaughter houses there will always be battlefields*." That is, as long as we are able to harm animals we are also capable of inflicting harm on other human beings (the differences between these species are not that big from a biological/genetic point of view (Orr, Masly, & Presgraves, 2004)). In sum, our ethical behaviour is closely linked to our philosophical Weltanschauung and non-dualism automatically fosters ethical virtues because it emphasises the organismic interconnectivity of nature (e.g., nature as a superorganism – a complex system perspective on all of life (Rosenberg & Zilber-Rosenberg, 2011)).

[192] The hitherto unsolved „hard problem" is: How is consciousness generated from matter? As Thomas Henry Huxley put it: "*How it is that anything so remarkable as a state of consciousness comes about as a result of irritating nervous tissue, is just as unaccountable as the appearance of the djinn when Aladdin rubbed his lamp in the story*." According to the philosophical position of „new mysterianism" the hard problem of consciousness can in principle not be resolved by human beings, i.e., it is „a mystery that human intelligence will never unravel" (McGinn, 2004). That is, human cognisers posses inherent epistemological limitations which prevent them to solve the quintessential and perenial mind-matter problem (in the same way an ant cannot know molecular genetetics due to its species-specific limitations).

context as indicated by "the measurement problem" in quantum physics (Hollowood, 2016; Schlosshauer, 2004).

6.10 Dṛg-Dṛśya-Viveka: An inquiry into the nature of the seers and the seen

In the context of psychophysics and nonduality, the Vedāntic scripture entitled "Dṛg-Dṛśya-Viveka[193]: An inquiry into the nature of the seers and the seen" is of particular pertinence. The text is primarily attributed Bĥaratī Tīrtha (circa 1350) who was the teacher of high priest Vidyāraṇya. It provides a cogent logical and rational analysis of the relation between the seer (Dṛg) and the seen (Dṛśya), viz., subject and object, the observer and the observed, the internal and the external, psychology and physics. That is, this inquiry is of great importance for an understanding of Advaita Vedānta philosophy and for the interface between psychology and physics. The very interesting and concise text is composed of only 46 ślokas श्लोक (i.e., poems in the style of Sanskrit poetry) and it has been descripted as an "excellent *vade mecum* for the study of higher Vedānta" (Nikhilananda, 1931; *vade mecum* being Latin for referential handbook). Bibliometrics distributions indicate that the number of books which are published every year is constantly increasing. For instance, in the last ten years, more books were published than all books published within the history of humanity taken together (a conservative estimate). However, the number of books which are relevant after millennia is minute and the number of books which are relevant after millennia is

[193] An English translation of the full text is available under the following URL: https://archive.org/details/drgdrsyaviveka030903mbp
In Sanskrit Dṛg means „seer" and Dṛśya „the seen". The term „viveka" (विवेक) means discernment, discrimination knowledge, or right understanding. In the context of Indian psychology it has been interpreted as a as sense of discrimination between the real and the unreal, between the self and the non-self, between the transient and the permanent (Rao & Paranjpe, 2016).

consequently much smaller. The Dṛg-Dṛśya-Viveka contains timeless knowledge which remains pertinent in the 21st century, i.e., it has a high degree of "memetic fitness" to use quasi-evolutionary terminology (cf. Kendal & Laland, 2000). The first śloka[194] of this profound philosophical text goes straight into the heart of the psychophysical subject-matter without wasting time on introductory preliminaries and it can be regarded as the most important part of the whole book. It has been translated from Sanskrit into English by Swami Nikhilananda (1931) as follows (traditionally the śloka would be chanted in Sanskrit[195] due to the importance of phonetics in language perception and processing[196], moreover, it would be memorised by the student in order to foster the slow process of intellectual understanding):

"*The form*[197] *is perceived and the eye*[198] *is its perceiver*[199]*. It (eye) is perceived and the mind*[200] *is its perceiver. The mind with*[201] *its modifications is perceived and the Witness (the Self) is verily the perceiver*[202]*. But It*[203] *(the Witness) is not perceived (by any other).*"

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[194] Shloka (Sanskrit: श्लोक śloka; can be translated as "song", etymologically derived from the root śru, "to hear") refers to a verse line or poem developed from the Vedic Anuṣṭubh poetic meter.
[195] The first śloka chanted in Sanskrit by Swami Sarvapriyananda in 2016 can be found under the following timestamped URL: https://youtu.be/c4gqTD_EPQY?t=753
[196] Interestingly from a neuroanatomical and psycholinguistic point of view, the syntactic and phonetic aspects of language perception are predominantly processed in the left hemisphere (Boca's area, i.e., pars triangularis and the pars opercularis of the inferior frontal gyrus) while prosodic and melodic aspects of language perception are processed in the contralateral right hemisphere (R. P. Meier & Pinker, 1995).
[197] Form — The word implies all objects of sense perception.
[198] Eye — It stands for all the organs of perception such as nose, ears, etc.
[199] Perceiver — The eye is perceiver only in a relative sense because it is itself perceived by the mind.
[200] Mind — The sense organs, unless the mind is attached to them, cannot perceive their objects. In a state of deep sleep, the sense organs do not perceive anything because the mind, at that time, ceases to function.
[201] With etc. — This includes Buddhi, Chitta, and Ahaṃkāra.
[202] Perceiver — The mind is controlled by the conscious Self.
[203]It — The Atman or the innermost Self is the ultimate perceiver. If a perceiver of the Ātman is sought, the enquiry will end in what is known as a *regressus ad infinitum*. All entities from the gross objects to the mind are products of Avidyā which itself is insentient. Hence, they also partake of the nature of insentiency. Therefore, they are objects. The subjective character of some of these is only relative. But the Self is the ultimate Seer because no other seer is known to exist. The knowledge of the Knower is never absent.

This śloka demonstrates that the mind is subject to perception. The quintessential question is: Who is perceiving the mind. According to Advaita Vedānta, the ultimate percipient is Ātman, the true-self.

The third śloka continues to analytically dissects the nature of perception described in the first śloka:

"*The eye, on account of its interchangeable nature, is an object and its perceiver is the mind*."

The fifth śloka further inquiries into the unity of consciousness and emphasised the distinction between mind and consciousness (a semantic distinction which is currently lacking in the majority of psychological discourses):

"*That the mind undergoes all these changes is known to all. Because of its changeable nature, the mind is an object of perception and Consciousness is the perceiver. This is because all the changes are perceived by Consciousness. Consciousness perceives all the states because it is a unity. These states, though distinct in nature, become unified in Consciousness or Self.*"

A more detailed discussion of the text goes beyond the scope of this thesis. We would like to suggest that, given the importance QM places on observation (e.g., the unresolved observer-problem which is central to the subject), a deeper conceptual analysis of the relation between the observer and the observed (an inquiry into the nature of the seer and the seen) seems to be a potentially fruitful path to a better understanding of the conceptual basis of QM and psychophysics in general. That is, a truly psychophysical analysis might help to begin to tackle the hard problem of consciousness which may turn out to be intimately related to the "enigma of QM"

(Rosenblum & Kuttner, 2002, 2011). Insights into the ultimate nature of perception are of utmost importance for a complete analysis of perceptual processes. Gustav Fechner (the founder of psychophysics) wrote extensively on the “world soul” or *anima mundi* (Greek: ψυχὴ κόσμου psuchè kósmou; discussed in the introduction of this theses)[204]. Fechner’s conception resembles the Vedāntic conception of universal consciousness (the same concept can also be found in Mahāyāna Buddhism (recall Niels Bohr’s affinity to Buddhistic symbolism in the context of quantum-physical complementarity and also the Pauli-Jung conjecture in the context of double-aspect monism). The same unified viewpoint has been formulated by the renowned Austrian quantum physicist and Nobel laureate and founder of quantum physics Erwin Schrödinger who was deeply impressed by Vedānta philosophy. He wrote in his seminal book “What is Life”:

“*The only possible alternative is simply to keep the immediate that consciousness is a singular of which the plural is unknown; that there is only one thing and that, which seems to be a plurality, is merely a series of different aspects of this one thing, produced by a deception (the Indian Maya); the same illusion is produced in a gallery of mirrors, and in the same way Gaurisankar and Mt. Everest turned out to be the same peak seen from different valleys…*” (Schrödinger, 1944, p. 89).

Schrödinger is not the only influential quantum physicist who postulates the primacy and continuity of consciousness. For instance, his eminent German colleague and fellow

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[204] Recall also the etymological definition of psychology as discussed previously: The ancient Greek word psukhḗ (ψυχή) or psyche means “life/soul/spirit” and also “breath”. Interestingly, breathing techniques are a central aspect of yoga, i.e., prāṇāyāma प्राणायाम, often translated as “extension of the prāṇa (breath or life force)”. The systematic “control of breath” enables the yoga practitioner to control the mind which is crucial for deeper mediation and self-discovery. From a linguistic point of view the Sanskrit word Ātman forms the basis for the German word “Atmen” which means “breathing”. Likewise, the Chinese symbol for "spirit, soul" is 魂 which also means “breath”. Hence, the linkage between “soul/spirit” and breath was formed independently by separate cultures. Thus defined, psychology is the study of “life/soul/spirit” and “breath”, i.e., Ātman.

Nobel laureate Max Planck (who coined the term "quantum") states in his speech on "Das Wesen der Materie" [The Nature of Matter]:

„*Als Physiker, der sein ganzes Leben der nüchternen Wissenschaft, der Erforschung der Materie widmete, bin ich sicher von dem Verdacht frei, für einen Schwarmgeist gehalten zu werden. Und so sage ich nach meinen Erforschungen des Atoms dieses: Es gibt keine Materie an sich. Alle Materie entsteht und besteht nur durch eine Kraft, welche die Atomteilchen in Schwingung bringt und sie zum winzigsten Sonnensystem des Alls zusammenhält. Da es im ganzen Weltall aber weder eine intelligente Kraft noch eine ewige Kraft gibt—es ist der Menschheit nicht gelungen, das heißersehnte Perpetuum mobile zu erfinden—so müssen wir hinter dieser Kraft einen bewußten intelligenten Geist annehmen. Dieser Geist ist der Urgrund aller Materie*." (Planck, 1944).

Translation:

"*As a man who has devoted his whole life to the most clear headed science, to the study of matter, I can tell you as a result of my research about atoms this much: There is no matter as such. All matter originates and exists only by virtue of a force which brings the particle of an atom to vibration and holds this most minute solar system of the atom together. We must assume behind this force the existence of a conscious and intelligent Mind. This Mind is the matrix of all matter*." (as cited in Pickover, 2008)

The English translation is not perfect and "Mind" should be translated as "Spirit" (Geist) – an important distinction. The same non-dual perspective as articulated by Schrödinger and Planck can be found back in several ancient Indian wisdom traditions. For example, the great scientist of the mind Patañjali writes in Sanskrit:

दृग्दर्शनशक्त्योरेकात्मतैवास्मिता ॥६॥

"To identify consciousness with that which merely reflects consciousness – this is egoism." (Yoga Sūtras of Patañjali, Chapter 2, Aphorism 6; Swami Prabhavananda trans., 1991; p.74).

According to quantum physicists Henry Stapp (who worked with Heisenberg and Wheeler) the wave function is made out of "mind stuff". Stapp became well known in the physics community for his work on S-matrix theory, nonlocality, and the place of free will in orthodox von Neumann quantum mechanics. Stapp argues that most contemporary physicists would explain that the wave-function is a vector in a linear Hilbert space. Stapp argues that this explanation points to the fact that the wave-function is not a material thing but a mental concept. It belongs to the realm of mind and not to the domain of matter. In classical Cartesian dualistic terminology: it belongs to the *res cogitans* and not to the *res extensa*.

According to the Cartesian framework it appears as if two players would be involved: the observer (the one who is asking the question) and the observed (i.e., matter/nature). However, according to Henry Stapp quantum theory combines this dichotomy between epistemology and ontology because it was realized that the only things that really existed were knowledge. That is, ontology is always defined by epistemology which is primary. In simple terms, knowledge (a faculty of the human mind) is primary and hitherto "objective" matter secondary. In a sense, quantum physics addressed a quintessential and long-standing philosophical problem, namely how epistemology and ontology interact and relate to each other. Thereby, quantum physics overcomes this dualistic notion inherited from western philosophy and merged the concepts into one integrated whole.[205]

A similar monistic perspective on the primacy of consciousness was advocated by Sir Arthur Eddington who argued that dualistic metaphysics (which form the unquestioned implicit basis of the large majority of contemporary scientific theories) are not supported by empirical evidence:

"*The mind-stuff of the world is, of course, something more general than our individual conscious minds. […] The mind-stuff is not spread in space and time; these are part of the cyclic scheme ultimately derived out of it. […] It is necessary to keep reminding ourselves that all knowledge of our environment from which the world of physics is constructed, has entered in the form of messages transmitted along the nerves to the seat of consciousness. […] Consciousness is not sharply defined, but fades into subconsciousness; and beyond that we must postulate something indefinite but yet continuous with our mental nature. […] It is difficult for the matter-of-fact physicist to accept the view that the substratum of everything is of mental character. But no one can deny that mind is the first and most direct thing in our experience, and all else is remote inference*." (Eddington, 1929, pp. 276–281)

This position clearly shows the importance of psychology in the scientific endeavour and specifically physics. Currently, physics is regarded as the science *par excellence*, even though it struggled hard to achieve this status which is partly due to the link

[205] Note that we are not trying to argue that the ancient advaitic tradition is scientifically supported by quantum physics. However, there are undeniable and interesting parallels between these widely separated fields of inquiry which both inquire into the ultimate nature of reality. The Upanishads (which form the scriptural basis of Advaita Vedānta) are to a large extend formulated in terms of poetry and metaphors (e.g., Brahman is often compared to the ocean). However, quantum physics also utilises metaphorical terms with oftentimes technical meaning, e.g., "quantum foam" (aka. spacetime foam) – a concept devised by theoretical physicist John Wheeler (Wheeler, 1955).

between physics and industrialism (Morus, 2005). However, given that science (and hence physics) is an activity which takes place within the human mind, psychology should be rank-ordered above physics (which is purely concerned with the physical world). It can be syllogistically argued that psychology is more primary than physics. It should be emphasised that psychological knowledge (self-knowledge in which the investigator becomes an object of knowledge himself) is much harder to obtain than knowledge about the external physical world (even though both are ultimately interrelated) due to the multi-layered and seemingly tautological complexities associated with introspective observations (as opposed to extrospective observations). Furthermore, the mere reliance on the outward directed senses organs neglects the human capacity of deep self-inquiry which leads to true insights about the nature of the self and existence (beyond the superficial constantly changing forms of appearance, cf. the Vedic concept of Māyā[206] माया, (R. Brooks, 1969)). Despite the difficulties associated with the endeavour of self-knowledge, we predict that this shift in emphasis (from physics to psychology) will be a defining feature of 21st century science. We are currently approaching a tipping-point (or phase-shift). This turning point is of immense importance because humanity needs to overcome the clearly detrimental, myopic, and superficial materialist paradigm in order to evolve and mature as a species as has been pointed out by countless sincerely concerned scholars. Currently humanity is lacking

[206] Māyā is an ancient Indian concept which connotes "that which exists, but is constantly changing and thus is spiritually unreal" (Hiriyanna, 1995). It has been roughly translated as illusion even though this translation has its shortcomings (translations from Sanskrit into English face many hermeneutical difficulties, another twofold Vedantic translation is "projection" and "veil"). Nobel laurate Erwin Schrödinger referred to the concept in his analysis of the unified nature of consciousness (see section 6.1). A connatural concept can arguably also be found in Plato's "Allegory of the cave" (Republic, 514a–520a). Plato was very much concerned with eternal forms and most mathematicians can be regarded as Platonists (Burnyeat, 2000; Mueller, 2005) even though they might not be explicitly aware of this philosophical heritage (cf. the importance of Δianoia in Plato's "Theory of Forms" (Cooper, 1966; Tanner, 1970)). Interestingly, Plato's allegory has recently been revived in the context of quantum dynamics and quantum computation, particularly with regards to the quantum Zeno effect (Misra & Sudarshan, 1977; Asher Peres, 1980; H. P. Stapp, 2001) and "projected" reality perceived through noncommutative "sequences of measurements" (but see Burgarth et al., 2014).

consciousness and self-awareness and this manifests in detrimental behaviour which seriously endangers the survival of the species. The “doomsday clock” which is since 1947 maintained by the “Bulletin of the Atomic Scientists' Science and Security Board” is presently set to “two minutes to midnight” which is closer to disaster (i.e., “technologically or environmentally-induced catastrophe”) than ever before in human history (Bostrom, 2008; Krauss, 2010). The evolution of consciousness is essential in this respect. If humanity wants to change its behaviour the species needs to evolve into a higher stage of consciousness. Insights into the unity of existence provide a firm basis for the evolution of human consciousness and the survival of the species (which is currently under severe threat). Moreover, the realisation of interconnectivity is crucial for the protection of the environment and biodiversity which is currently under enormous threat. We are currently causing the 6^{th} mass extinction (Berkhout, 2014; Crutzen, 2006; Lewis & Maslin, 2015), i.e., the first human-caused (anthropogenic) global mass extinction (collapse of biodiversity). Western science has made great progress in manipulating the external physical world, however, from a psychological it is extremely immature, primitive, and underdeveloped (a dangerous and volatile combination, think about nuclear weapons in the hands of ego-driven, greedy, and aggressive political leaders – e.g., Hitler in Nazi Germany). In other words, humanity is technologically highly developed, but its psychological development lacks far behind. Our misconception of the nature of self leads to irrational decisions with far reaching consequences. The strong identification with the ego is a driving force behind many detrimental behaviours. A dissociation from the ego-identity and an association with a more inclusive level of consciousness would provide a much more solid basis for planned and reflective behaviour. It cannot be denied that humanity is currently in a crisis and this crisis is ultimately caused by a lack of consciousness and awareness. The behavioural manifestations are just symptoms of a much deeper psychological/spiritual deficit. All behaviour is based on thought and thought is largely determined by perceptual inputs. Therefore, humanity needs to change its ways of perceiving and thinking (mental hygiene[207]) in order to address the behavioural deficits. Realisations of unity (the unity of humanity as a species) are extremely important for moral and ethical reasons and for our understanding of human psychology (which is currently extremely limited due to the ego-boundedness of the predominant materialistic paradigm). The same holds true for the realisation of the unity and intimate interconnectedness of all living beings (cf. the hologenome theory of evolution and symbiogenesis (Rosenberg, Sharon, & Zilber-Rosenberg, 2009; Rosenberg & Zilber-Rosenberg, 2008, 2011)). Our primitive psychology lies at the very heart of the anthropogenic mass-extinction humanity is currently causing (i.e., the so called "holocene extinction" (Harrison, 1984; Johnson & Wroe, 2003; Newbold et al., 2016; Stuart, Kosintsev, Higham, & Lister, 2004; Worm et al., 2006a)). If *homo sapiens* does not evolve to a more inclusive level of consciousness (which entails deep realisation of the interconnectedness of nature and the importance of biodiversity, e.g., biophilia) our chances of survival are extremely low.

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[207] We take great care of what we are eating, and bodily hygiene plays an important role in everyday life. However, our senses are exposed to very unhealthy inputs which are oftentimes systematically designed to misguide us (e.g., the PR industry and the mass-media (P. Bernays, 1928; Chomsky, 1992; L'Etang, 1999)). We therefore need to rigorously control our mental contents (Chomsky uses the phrase "mental self-defence", otherwise the resulting behaviour will be of low quality (a simple input→output relation in the scheme of behaviouristic S→R psychology). However, because many systematic psychological manipulations (e.g., Cambridge Analytica, 2017- a company which combines data anlytics with behavioural economics and which former director of research Christopher Wylie described as "a full blown propaganda machine") explicitly target the unconscious mind, i.e, System 1 processes to use the terminology of contemporary behavioural economics (but see Chomsky, 1992; P. Fleming & Oswick, 2014; Mullen, 2010; Mullen & Klaehn, 2010), mental self-defence is oftentimes extremely difficult. Introspective mediation is thus a critical tool in this respect in order to inspect and scrutinise the contents of the mind. If we unreflectively and naively identify the self with the contents of our mind we lose the necessary metacognitive degrees of freedom which would allow us to interfere with its contents.

We would also like to emphasise the pertinence of other knowledge sources for psychophysics. In the same way mathematics (Kerala school of mathematics), logic (Vedanta logic), and linguistics[208] were inspired by particularly Vedāntic traditions, Psychophysics can do as well (e.g., the concept of nonduality, panpsychism, and panentheism).

Swami Vivekananda articulates the following on psychophysical complementarity (even though he does not use this specific nomenclature) in one of his excellent lectures on "practical Vedānta" which he delivered in London in 1896:

"*There are two worlds, the microcosm, and the macrocosm, the internal and the external. We get truth from both of these by means of experience. The truth gathered from internal experience is psychology, metaphysics, and religion; from external experience, the physical sciences. Now a perfect truth should be in harmony with experiences in both these worlds. The microcosm must bear testimony to the macrocosm, and the macrocosm to the microcosm; physical truth must have its counterpart in the internal world, and the internal world must have its verification outside. Yet, as a rule, we find that many of these truths are in conflict. At one period of the world's history, the internals become supreme, and they begin to fight the externals. At the present time the externals, the physicists, have become supreme, and they have put down many claims of psychologists and metaphysicians. So far as my knowledge goes, I find that the real, essential parts of psychology are in perfect accord with the essential parts of modern physical knowledge. It is not given to one individual to be great in every respect; it is not given to one race or nation to be equally strong in the research of all fields of knowledge. The modern European nations are very strong in*

[208] For instance, the influence of the ancient Sanskrit philologist and grammarian Pāṇini on Noam Chomsky's influential theories.

their research of external physical knowledge, but they are not so strong in their study of the inner nature of man. On the other hand, the Orientals have not been very strong in their researches of the external physical world, but very strong in their researches of the internal. Therefore we find that Oriental physics and other sciences are not in accordance with Occidental Sciences; nor is Occidental psychology in harmony with Oriental psychology. The Oriental physicists have been routed by Occidental scientists. At the same time, each claims to rest on truth; and as we stated before, real truth in any field of knowledge will not contradict itself; the truths internal are in harmony with the truths external. ... What we call matter in modern times was called by; the ancient psychologists Bhutas, the external elements. There is one element which, according to them, is eternal; every other element is produced out of this one. It is called Âkâsha." (Vivekananda, 1896)

6.11 Statistical considerations

6.11.1 General remarks on NHST

Statistics has been called "the grammar of science" (Cumming, 2012) and inferential reasoning processes lie at the very heart of scientific research. Currently, Fisherian null hypothesis significance testing is the dominant (orthodox) inferential method in most scientific disciplines (Fisher himself was a geneticist). As mentioned before, it is a robust empirical finding that the underlying Aristotelian syllogistic logic of NHST is ubiquitously misunderstood, not just by students, but also by their statistics lecturers (e.g., Haller & Krauss, 2002), by professional academic researchers (e.g., Rozeboom, 1960), and even by professional statisticians (e.g., Lecoutre, et al., 2003). That is, unsound logical thinking and wrong knowledge and beliefs concerning NHST are omnipresent in the scientific community. Peer-reviewed scientific publications, textbooks, lecturers, and high-ranking professionals perpetuate the misinterpretations of NHST, i.e., they hand down the Fisherian/Neyman-Pearsonian hybrid meme to the next generation of researchers. The cognitive bias "appeal to authority" (Goodwin, 1998, 2011) likely plays a pivotal role in this context (in logics known as *argumentum ad verecundiam*), as does the widely studied "expertise heuristic" (Chaiken & Maheswaran, 1994; Reimer, Mata, & Stoecklin, 2004). Both can be categorised as System 1 processes in the dual-system framework (Jonathan St B.T. Evans & Stanovich, 2013) discussed earlier and are therefore automatic, "fast and frugal" (Gerd Gigerenzer & Goldstein, 1996) reasoning processes. It requires conscious cognitive effort in order to overcome these implicit processes (Muraven & Baumeister, 2000). It has been vehemently argued that "Yes, Psychologists Must Change the Way They Analyze Their Data" (E. J. Wagenmakers, Wetzels, Borsboom, & Maas, 2011) and this change needs to be implemented through active cognitive effort (System 2). To adopt Kantian phraseology, psychologists need to wake up from their "dogmatic slumber".

A recent article entitled "The prevalence of statistical reporting errors in psychology (1985–2013)" (Nuijten, Hartgerink, van Assen, Epskamp, & Wicherts, 2016a) reported that circa 50% of all published psychology articles contained at least one erroneous *p*-value (i.e., a *p*-value inconsistent with the associated test statistic). The authors extracted textual data (HTML and PDF) from a number of APA flagship journals using the R package "`statscheck`"[209] and recomputed the published *p*-values. This allowed an automated large-scale analysis of *p*-value reporting. The authors warned that the "alarming high error rate can have large consequence". Previous studies found that a

[209] The manual of the package and installation-routine can be accessed under the following URL: https://cran.r-project.org/web/packages/statcheck/statcheck.pdf

higher prevalence of statistical errors was associated an unwillingness to share data on part of the authors (Wicherts, Bakker, & Molenaar, 2011). Questionable research practices (QRPs) in psychology have been discussed from various perspectives (John, Loewenstein, & Prelec, 2012). Prevalent QPRs involve the failure to report all dependent variables and/or all experimental conditions and not adhering to required data collection stopping rules ("data peeking"). Moreover, research shows that the number of negative reported results is declining in various scientific disciplines, i.e., "negative results are disappearing from most disciplines" (Fanelli, 2012) and that logical/statistical inconsistencies and "just significant *p*-values" are becoming more prevalent (N. C. Leggett, Thomas, Loetscher, & Nicholls, 2013).

Interestingly, the "`statcheck`" analysis found that the search queries "Bonferroni" and "Huynh-Feld" (terms associated with α-corrections for multiple comparisons) were only found in 9 articles in a sample of more than 30000 articles (i.e., 0.3% of the total sample of psychology studies). On average, the number of NHST results per paper had a median value of 11 (which implies that the average α-value should be significantly reduced, depending on the exact correction procedure. For instance, a classic stepwise Bonferroni correction would divide the α-value by 11, resulting in a p-value of ≈ 0.0045. This result indicates that corrections for multiple comparisons are rarely applied even though it is arguable a mandatory statistical technique to counteract α-inflation. Furthermore, the authors reported a significant *p*-value was statistically more likely to be "grossly inconsistent" than nonsignificant *p*-values. One can only speculate about the underlying reasons. The "`statscheck`" meta-analysis is consistent with previous studies which focused on this fundamental issue (Bakker & Wicherts, 2011; Berle & Starcevic, 2007; García-Berthou & Alcaraz, 2004). Moreover, despite the longstanding criticism, the use of NHST in psychology seems to have increased. Our own

GoogleTrends analysis using the R packages "`ngramr`" (see Figure 78) and "*gtrendsR*" verified this worrisome rising trend.

Distorted *p*-values can lead to fallacious conclusions, which in turn can lead to irrational real world decisions. Moreover, they distort meta-analytical research and systematic reviews. Analytical reviews (AR) have been suggested as a strategy to counteract inconsistent *p*-values (Sakaluk et al., 2014). AR require authors to submit their data alongside with the syntax which was used for the associated analysis is (currently the APA merely requires authors to provide data if they are explicitly asked for the purpose of verification). Sharing data has many advantages – for instance for the purpose of data aggregation (which can be done by Ai, e.g., machine learning algorithms (Wojtusiak, Michalski, Simanivanh, & Baranova, 2009)). The AR approach allows reviewers to double-check whether the reported test statistics are accurate. However, this requires a lot of extra work on the part of the reviewers (and is therefore perhaps an unrealistic demand). Automated software like the "`statscheck`" R package can facilitate this task. Moreover, the "co-pilot model" (Wicherts, 2011) published in NATURE has been suggested as a potential remedy (i.e., multiple authors conducting and verifying the analysis). Along this line of thought, we argue, that the concept of interrater reliability (as advocated by many methodologists) is a standard in much psychological research and should be applied to psychological analysis.

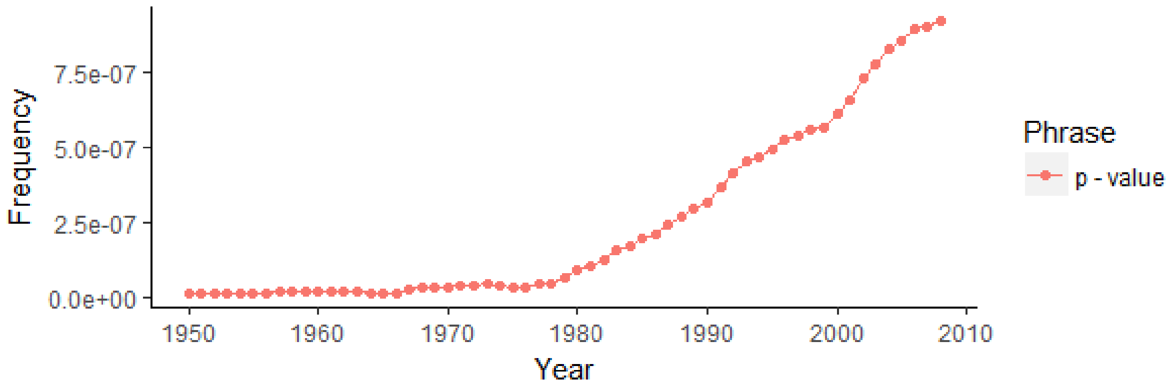

Figure 78. Graph indicating the continuously increasing popularity of *p*-values since 1950.

Note: *Data was extracted from the Google Books Ngram corpus with the R package “ngramr” (Lin et al., 2012).*

We created a website which contains additional information on the logical fallacies associated with NHST. The website is available under the following URL: http://irrational-decisions.com/?page_id=441#nhst

To sum up this brief discussion of statistical methods, it can be concluded that NHST is a methodological *de facto* standard which has been deeply implanted in the minds of researchers over several generations. The critical facts about it are as old as its invention (as the historical debate between Fischer versus Neyman/Pearson exemplifies). The issue is not rational — it is irrational in nature. Most practicing researchers are not very interested in discussing “nonpragmatic” statistical problems. They rather conform to the predominant norm and use the methods that have been given to them and which are regarded as the *sine qua non* for the field of research they work in (conformity might be associated with a lack of introspective reflection, intrinsic motivation, and epistemological curiosity, and perhaps scientific integrity, *inter alia*). Unconscious motives play a pivotal role in this context as most decisions are not based on conscious reflections but on unconscious processes. The problems associated with the use of *p*-values are much more psychological and social than mathematics. *P*-values are deeply ingrained in the methods of psychology, the bio-medical sciences, and countless other scientific disciplines. The "Platonic-fallacy" is to assume that the decision which inferential methods are utilised are based on rationality. The more complex the discussed methods are from a mathematical point of view, the larger the divide between System 1 (habitual) and System 2 processes (logic). The issue is thus psychological in nature. We need to investigate why researchers are applying these methods in a ritualistic non-reflective manner. What are their intentions and motivations. Indeed, it can be argued that the *p*-ritual is reminiscent of OCD (Obsessive Compulsive Disorder) symptomology and it would be interesting to investigate the comorbidity and whether a significant proportion of the neural correlates are overlapping, e.g., dopaminergic dysfunction in cortico-striatal-thalamic-cortical circuits (J. Wood & Ahmari, 2015). The *p*-ritual has been institutionalised — consequently conformity to group norms and obedience to authority play a central role. Moreover, the aforementioned systemic incentive structure (i.e., publish or perish, the reliance on quantitative publication indices to evaluate scholars, job insecurity, etc. pp.) play an important psychological role in this context. It is not primarily a mathematical/logical problem but a psychological/social one and the "extralogical factors" need to be addressed with the same rigour if we want to tackle the current "statistical crisis" effectively. We argue that "radical" measures need to be taken (the term radical is etymologically derived from the Latin "radix" meaning "root"). That is, the root of the statistical crisis is primarily psychological and not statistical (cf. G Gigerenzer, 1993) and therefore the root causes need to be addressed instead of fruitless attempts to alleviate superficial symptomological manifestations of the underlying issue. Recently, a new diagnostic category according to various DSM-V criteria has been proposed in this context: "pathological publishing" (Buela-Casal, 2014). Several diagnostic criteria which are summarised in

Table 37 have been proposed. Others have argued along the same lines — during the development of the DSM-V it was ironically proposed that a “disorder covering scientists addicted to questionable research practices” should be included in order to deal with the “emerging epidemic of scientists engaging in questionable research practices”. The following diagnostic criteria were formulated: “The essential feature of pathological publishing is the persistent and recurrent publishing of confirmatory findings (Criterion A) combined with a callous disregard for null results (Criterion B) that produces a ‘good story’ (Criterion C), leading to marked distress in neo-Popperians (Criterion D)” (Gullo & O’Gorman, 2012, p. 689). The “impact factor style of thinking” (Fernández-Ríos & Rodríguez-Díaz, 2014) has been proposed as a new theoretical framework which is pertinent in this context (viz., “assessing publications on the basis of the impact factor”, “university policy habitus obsessed impact index”). Currently, scientific content that has not been published in a journal that is indexed in impact factor databases such as those underlying the Journal Citation Reports (JCR) is academically not relevant. This has led to phenomena such as the “impact factor game” and systematic impact factor manipulation (Falagas & Alexiou, 2008). The topic has been discussed in some detail in a recent NATURE article entitled: “Beat it, impact factor! Publishing elite turns against controversial metric” (E. Callaway, 2016).

Table 37

Potential criteria for the multifactorial diagnosis of "pathological publishing" (adapted from Buela-Casal, 2014, pp. 92–93).

A. Having an excessive eagerness to show, disseminate, and advertise one's articles. This is reflected in a compulsive behaviour that consists of including one's publications and indicators of one's publications in numerous devices that are listed below.

B. Falsifying articles including false or manipulated data in articles to obtain more publications or publish in journals with a higher impact factor.

C. Falsifying one's CV including records of papers that are not such or duplicating articles.

D. Distorting reality believing the data that one has falsified or manipulated.

E. Distorting reality believing that something is an article when it is not (e.g., book reviews, meeting abstracts, editorial material, proceeding papers, notes). Internet devices where indicators of publications are advertised:

1) ResearchGate
2) Scopus Author Identifier
3) WoS ResearcherID
4) Google Scholar profile
5) ORCID (Open Researcher and Contributor ID)
6) Twitter profile
7) Facebook profile
8) Linkedin profile
9) Mendeley profile
10) Delicious profile
11) Microsoft Academic Search profile
12) Academia.edu profile
13) CiteULike
14) Author Resolver™ (from Scholar Universe)
15) INSPIRE, the High Energy Physics information system
16) RePEc (Research Papers in Economics)
17) IraLIS (International Registry of Authors-Links to Identify Scientists).
18) Vivoweb profile
19) Blogger profile
20) Etc. pp.

F. Signing up for citation alerts

G. Really Simple Syndication (RSS)

H. Having e-mailing lists such as IweTel or Incyt

I. Calculating one's h-index and updating it frequently

J. Counting citations to one's work and updating the number frequently.

K. Counting article downloads

L. Calculating the cumulated impact factor and updating it frequently.

M. Publishing anything to increase the number of publications

N. Continuously updating one's CV

O. Including one's CV and various indicators of the CV in a personal web page.

P. Including ResearcherID or other indicators in web pages that include the production of colleagues.

Q. Using Web 2.0 to increase the number of citations

In addition to systemic and psychological interventions which change the extrinsic reinforcement schedule of academia and facilitate intrinsic motivation and altruistic behaviour, we suggest that various Bayesian methods can be successfully combined with preregistration[210] of studies (C. Chambers, 2013, 2014; McCarron & Chambers, 2015), a proposal which has previously been formulated in the context of "neuroadaptive Bayesian optimization and hypothesis testing" (see Lorenz, Hampshire, & Leech, 2017). Preregistration is a novel publishing initiative and provides an important procedure that fosters transparency of research, mitigates publication bias, and enhances the reproducibility of research results because researcher specify their research strategies and planned hypothesis tests *a priori* before the research results are disseminated which enhances trust in the research conclusions. That is, the underlying motivation for conducting the study is explicitly disclosed prior to the analysis of the data which counters illegitimate HARKing (HARK is a backronym for "Hypothesizing After the Results are Known") (Kerr, 1998) and the use of (unfortunately) pervasive data mining techniques like *a posteriori* *p*-hacking as discussed earlier (i.e., data dredging, data fishing, data snooping) (Head, Holman, Lanfear, Kahn, & Jennions, 2015; Simonsohn, 2014; Simonsohn, Nelson, & Simmons, 2014; Veresoglou, 2015).

[210] Preregistration is the practice of publishing the methodology of experiments before they begin. This strategy reduces problems stemming from publication bias and selective reporting of results.
See for example:
https://aspredicted.org/
https://cos.io/prereg/
https://www.psychologicalscience.org/publications/replication
A examplary list of currently preregistered studies can be found on Zotero:
https://www.zotero.org/groups/479248/osf/items/collectionKey/KEJP68G9?

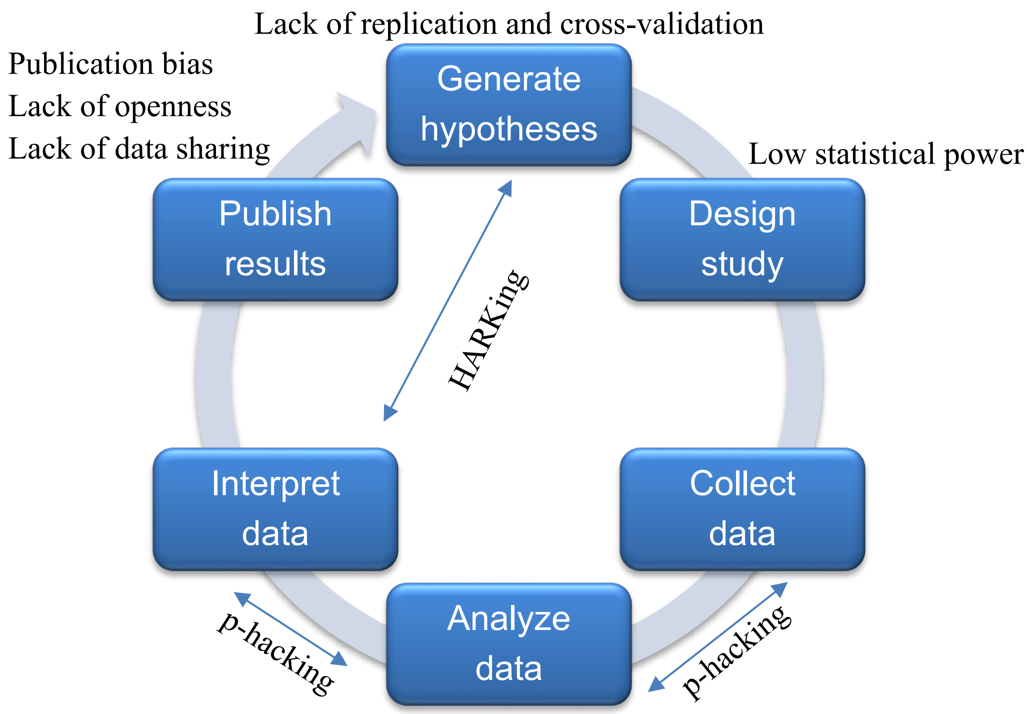

Figure 79. Questionable research practices that compromise the hypothetico-deductive model which underpins scientific research (adapted from C. D. Chambers, Feredoes, Muthukumaraswamy, & Etchells, 2014).

An excellent article on the topic published in AIMS NEUROSCIENCE is titled “Instead of ‘playing the game’ it is time to change the rules”. The recommended article is freely available under the appended URL.[211] It is self-evident that such opportunist research/analysis strategies as HARKing and *p*-hacking seriously compromise the evolution, progress, veracity, and trustworthiness of science. Preregistration thus prevents illegitimate *post-hoc* hypothesis testing procedures because hypotheses, methods, and analysis protocols are prespecified prior to conducting the study. Another key advantage of preregistration is that it enhances the quality of research due to an initial external review of the research methodology (there are alternative preregistration models which do not employ a review process (but see van ’t Veer & Giner-Sorolla,

[211] Instead of “playing the game” it is time to change the rules: Registered Reports at AIMS Neuroscience and beyond — https://orca.cf.ac.uk/59475/1/AN2.pdf

2016)). Preregistration is a measure which attenuates the problem of publication bias because information concerning statistically non-significant experiments becomes available to the research community and can be utilised for meta-analytical research purposes. That is, negative scientific results that are compatible with the null-hypothesis can be published (after peer reviewed quality checks are met) without regard to an arbitrary statistical significance threshold. However, it should be noted that preregistration is not appropriate for purely exploratory research (e.g., exploratory factor analysis using structural equation modelling, etc.), i.e., exploratory and confirmatory analyses are complementary. Most statistical methods are only valid for confirmatory research and are not designed for exploratory research and researchers should therefore commit to a specific analytic technique prior to consulting the data. With preregistration this crucial commitment is made before the data is collected. A procedure which clearly enhances the credibility of research. In the same vein, it has been argued that a stronger focus on confirmatory analyses reduces the "fairy tale factor" in scientific research (E. J. Wagenmakers, Wetzels, Borsboom, van der Maas, & Kievit, 2012). Hence, whenever a researcher wants to test prespecified hypotheses/predictions preregistration is a highly recommended approach to enhance the reliability, validity, veracity, and hence credibility of scientific research. Preregistration is crucial in order to be able to demarcate "hypothesis testing" from "hypothesis generation", i.e., the oftentimes blurry distinction between prediction versus postdiction.

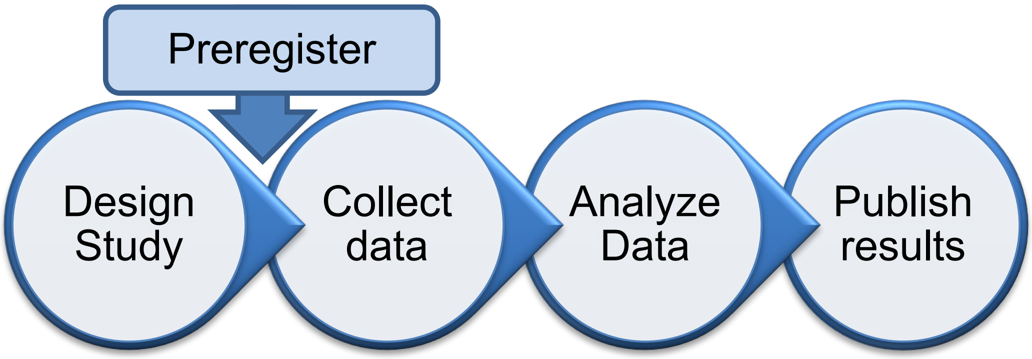

Figure 80. Flowchart of preregistration procedure in scientific research.

In the psychological literature on reasoning and decision-making "hindsight-bias"[212] is a widely studied phenomenon (Christensen-Szalanski & Willham, 1991; Hertwig, Gigerenzer, & Hoffrage, 1997; Hoffrage et al., 2011; Pohl, 2007; Pohl, Bender, & Lachmann, 2002; Roese & Vohs, 2012). Researchers are not immune to this ubiquitous automatic cognitive bias (a System 1 process, to employ dual-systems terminology). Consequently, it also applies to inferential decision-making in various statistical research scenarios. Explicit awareness of the hindsight-bias (and multifarious other cognitive biases which compromise reasoning) is thus of pivotal importance. Consequently, researcher should be educated about the general internal workings of their own minds (the instrument which does science). The well-documented psychology of thinking and reasoning is of particular importance in this regard (Jonathan St B T Evans, 2008; Kahneman, Slovic, & Tversky, 1982; K. E. Stanovich, 1999). However, given the automatic nature of most cognitive biases, awareness is not sufficient because prefrontally localised executive functions (System 2) which might help to regulate these

[212] "Hindsight bias occurs when people feel that they "knew it all along," that is, when they believe that an event is more predictable after it becomes known than it was before it became known." (Roese & Vohs, 2012, p. 411)

automatisms are based on limited cognitive resources which are costly in physical energetic terms, e.g., top-down regulation — glucose utilisation — ego-depletion (Baumeister, Bratslavsky, Muraven, & Tice, 1998). Therefore, we need to implement additional external systems which help to prevent such predictable fallacies. Preregistration is a systematic procedural intervention which directly antagonises unconscious biases which may distort scientific reasoning and decision-making (which in turn forms the basis of many important real-world decisions). In a publication in the Proceedings of the National Academy of Sciences, this novel trend has been termed "The preregistration revolution" (Nosek, Ebersole, DeHaven, & Mellor, 2018). Preregistration services (mainly web-based) are now becoming available for all scientific disciplines and should soon be widely adopted by the general research community.

6.11.2 The syllogistic logic of NHST

From a logical point of view NHST is based upon the logic of conditional syllogistic reasoning (Cohen, 1994). Compare the following syllogisms of the form *modus ponens*:

Syllogism 1

1st Premise:

If the null hypothesis is true, then this data (D) cannot occur.

2nd Premise:

D has occurred.

Conclusion:

∴ H_0 is false.

If this were the kind of reasoning used in NHST then it would be logically correct. In the Aristotelian sense, the conclusion is logically valid because it is based on deductive proof (in this case denying the antecedent by denying the consequent). However, this is not the logic behind NHST. By contrast, NHST uses hypothetical syllogistic reasoning (based on probabilisties), as follows:

Syllogism 2

1st Premise:

If H_0 is true, then this data (D) is highly unlikely.

2nd Premise:

D has occurred.

Conclusion:

$\therefore$ H_0 is highly unlikely.

By making the major premise probabilistic (as opposed to absolute, cf. Syllogism 1) the syllogism becomes formally incorrect and consequently leads to an invalid conclusion. The following structure of syllogistic reasoning is implicitly used by many authors in uncountable published scientific articles. This logical fallacy has been termed the “the illusion of attaining improbability”. (Cohen, 1994, p.998).

Syllogism 3

1st Premise:

If H_0 is true, then this data (D) is highly unlikely.

2nd Premise:

D has occured

Conclusion:

∴ H_0 is probably false.

Note: $\mathbf{p(D|H_0) \neq p(H_0|D)}$

6.11.3 Implications of the ubiquity of misinterpretations of NHST results

Given that inferential statistics are at the very heart of scientific reasoning it is essential that researchers have a firm understanding of the actual informative value which can be derived from the inferential techniques they employ in order to be able to draw valid conclusions. Future studies with academicians and PhD students from different disciplines are needed to determine the "epidemiology" of these doubtless widespread statistical illusions. The next sensible step would be to develop and study possible systematic interventions and their effectiveness (but see Lecoutre et al., 2003). We suggest that it is very necessary to invest in the development of novel pedagogical concepts and curricula in order to teach the misleading logic behind NHST to students. Moreover alternative statistical methods should be taught to students given that there is no "magic bullet" or "best" inferential method *per se*. Gigerenzer (1993) points out that "it is our duty to inform our students about the many good roads to statistical inference that exist, and to teach them how to use informed judgment to decide which one to follow for a particular problem" (p. 335). We strongly agree with this proposition. The "new Bayesian statistics" (Kruschke & Liddell, 2017a) provide a viable alternative to the Fisherian/Neyman-Pearsonian hybrid and researchers should be given the appropriate training to be able to understand and sensibly utilise these powerful non-frequentist methods.

6.11.4 P_{rep}: A misguided proposal for a new metric of replicability

We discussed the prevalent "replication fallacy" (G Gigerenzer, 1993) in the previous section. In order to provide a genuine numerical indicator of replicability a new metric called p_{rep} has been proposed (Killeen, 2005b). Its primary objective is to provide an estimate of replicability that does not involve Bayesian assumptions with regards to *a priori* distributions of θ. The submission guidelines of the APA flagship journal PSYCHOLOGICAL SCIENCE for some time explicitly encouraged authors to "use p_{rep} rather than *p*-values" in the results section of their articles. This fact is documented in the internet archive,[213] a digital online-database that provides a mnemonic online system containing the history of the web, a "digital time machine" (Rackley, 2009; Rogers, 2017). However, this official statistical recommendation by PSYCHOLOGICAL SCIENCE has now been retracted (but the internet never forgets…). By default, the p_{rep} metric is based upon a one-tailed probability value of test statistic T (but it can be used for F-test as well). However, this default can be changed into a two-tailed computation.

Equation 9. Formula to calculate P_{rep} (a proposed estimate of replicability).

[213] The URL of the relevant internet archive entry which documents the APA recommendation is as follows.
https://web.archive.org/web/20060525043648/http://www.blackwellpublishing.com/submit.asp?ref=0956-7976

$$p_{\text{rep}} = [1 + (\frac{p}{1-p})^{\frac{2}{3}}]^{-1}$$

The mathematical validity of p_{rep} has been seriously called into question (Doros & Geier, 2005). Based on the results of simulation studies, it has been convincingly argued that "p_{rep} misestimates the probability of replication" and that it "is not a useful statistic for psychological science" (Iverson, Lee, & Wagenmakers, 2009). In another critical reply to Killeen's proposal, it has been suggested that hypothesis testing using Bayes factor analysis is a much more effect strategy to avoid the problems associated with classical *p*-values (E.-J. Wagenmakers & Grünwald, 2006). One of the main shortcoming of the suggested new metric is that p_{rep} does not contain any new information 'over and above' the *p*-value — it is merely an extrapolation. Another weakness is that *a priori* information (for example knowledge from related previous studies) cannot be incorporated. Killeen responds to this argument with the "burden of history argument", i.e., each result should be investigated in isolation without taking any prior knowledge into account (viz., he advocates uniform priors). However, on logical grounds it is highly questionable whether a single study can be used as a basis for estimating the outcome of future studies. Various confounding factors (e.g., an unanticipated *tertium quid*) might have biased the pertinent results and consequently lead to wrong estimates and predictions. According to aphoristic "Sagan standard": Extraordinary claims require extraordinary evidence.[214] The novel p_{rep} metric does not align with this Bayesian philosophy. From our point of view, the main advantage to report and discuss p_{rep} is that it helps to explicate and counteract the ubiquitous "replication fallacy" (G Gigerenzer, 2004) associated with conventional *p*-value. The replication fallacy describes the widespread statistical illusion that the *p*-value contains

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[214] Pierre-Simon Laplace formulated the same proportional principle: „The weight of evidence for an extraordinary claim must be proportioned to its strangeness" (Flournoy, 1899).

information about the replicability of experimental results. In our own survey at a CogNovo workshop the "replication fallacy" was the most predominant misinterpretations of *p*-values. 77% (i.e., 14 out of 18) of our participants (including lecturers and professors) committed the replication fallacy. Only one participant interpreted the meaning of *p*-values correctly, presumably due to random chance. In a rejoinder titled "Replicability, confidence, and priors" (Killeen, 2005b) Killeen addresses several criticisms in some detail, particularly with regards to the stipulated nescience[215] of δ. Indeed, it has been argued that "replication probabilities depend on prior probability distributions" and that Killeen's approach ignores this information and as a result, "seems appropriate only when there is no relevant prior information" (Macdonald, 2005). However, in accordance with the great statisticians of this century (e.g., Cohen, 1994, 1995; Meehl, 1967), we argue that the underlying syllogistic logic of *p*-values is inherently flawed and that any attempt to rectify *p*-values is moribund. It is obvious that there is an urgent and long due "need to change current statistical practices in psychology" (Iverson et al., 2009). Creative change and innovation is vital to resolve the "statistical crisis" (Gelman & Loken, 2014; Loken & Gelman, 2017b). The current academic situation is completely intolerable and the real-world ramifications are tremendously wide and complex. New and reflective statistical thinking is urgently needed, instead of repetitive "mindless statistical rituals", as Gerd Gigerenzer[216] put it (G Gigerenzer, 1998, 2004). However, deeply engrained social

[215] In the semantic context at hand, nescience (etymologically derived from the Latin prefix *ne* "not" + *scire* "to know" cf. science) means "lacking knowledge" which is a more appropriate term than ignorance (which describes an act of knowingly ignoring). Unfortunately, linguistic diversity is continuously declining. A worrisome trend which is paralleled by a loss of cultural and biological diversity (Maffi, 2005; Worm et al., 2006b), *inter alia*.
[216] Gigerenzer is currently director of the "Center for Adaptive Behavior and Cognition" at the Max Planck Institute in Berlin. In his article entitled "Mindless Statistics" Gigerenzer is very explicit with regards to the NHST ritual: "*It is telling that few researchers are aware that their own heroes rejected what they practice routinely. Awareness of the origins of the ritual and of its rejection could cause a virulent cognitive dissonance, in addition to dissonance with editors, reviewers, and dear colleagues.*

(statistical) norms are difficult to change, especially when large numbers of researchers have vested interests to protect the prevailing methodological *status quo* as they were predominantly exclusively trained in the frequentist framework (using primarily the proprietary software IBM® SPSS). Hence, a curricular change is an integral part of the solution. Statistical software needs to be flexible enough to perform multiple complementary analysis. Until recently, SPSS did not provide any modules for Bayesian analyses even though the IBMs developers could have easily implemented alternative statistical methods to provide researchers with a more diverse statistical toolbox. Open-source software clearly is the way forward. The open-source community is highly creative and innovative. For instance, CRAN now host < 10000 packages for R and all kinds of sophisticated analyses can be conducted within the R environment. IBM is aware of the rise of open-source software (which is obviously seen as a fierce competitor for market shares). Presumably in reaction to the changing economic pressures, SPSS is now able to interface with R and Bayesian methods are now becoming available for the first time. Moreover, Markov chain Monte Carlo methods will become available in future versions of SPSS. All of this could have been realised much earlier. However, given the rapid upsurge of R, SPSS is now practically forced to change its approach towards (i.e., exnovation) in order to defend market shares (a passive/reactive approach, i.e., loss aversion (Novemsky & Kahneman, 2005)).

To conclude this important topic, it should be emphasised that rational approaches vis-à-vis problems associated with replicability, confidence, veracity, and the integration of prior knowledge are pivotal for the evolution and incremental progress of science. It is obvious that the fundamental methods of science are currently in upheaval.

Suppression of conflicts and contradicting information is in the very nature of this social ritual." (G Gigerenzer, 2004, p. 591)

6.11.5 Controlling experimentwise and familywise α-inflation in multiple hypothesis testing

In our experiments we tested several statistical hypotheses in a sequential manner. Whenever a researcher performs multiple comparisons, α-error control is of great importance[217] (Benjamini & Braun, 2002; Benjamini & Hochberg, 1995a; Holland & Copenhaver, 1988; Keselman, Games, & Rogan, 1979; Seaman, Levin, & Serlin, 1991; Simes, 1986; Tukey, 1991). However, empirical data indicates that most researchers completely neglect this important statistical correction (Nuijten, Hartgerink, van Assen, Epskamp, & Wicherts, 2016b). An α-error (also known as "Type I error") occurs when a researcher incorrectly rejects a true null hypothesis. On the other hand, a β-error ("Type II error") is inversely related to the probability of committing an α-error, i.e., incorrect acceptance of a false null hypothesis (see

[217] This does not apply to Bayesian hypothesis testing and parameter estimation approaches.

Table 38). In every situation in which multiple tests are performed the α-error rate is inflated in proportion to the number of hypothesis tests performed. R.A. Fisher discussed this central problem in his seminal book *The Design of Experiments* (R. A. Fisher, 1935), which laid the foundation for modern statistical hypothesis testing as utilised in the majority of scientific and bio-medical disciplines. He proposed the “Least Significant Difference” (LSD) procedure in order to counteract α-inflation (L. J. Williams & Abdi, 2010). LSD has been criticized for not being conservative enough in many situations and its “liberalness” has been demonstrated in mathematical simulation experiments (using Monte Carlo methods) which specifically focused on pairwise comparisons of two means (Boardman & Moffitt, 1971). Since Fisher’s early attempt, countless alternative multiple comparison error rate control procedures have been invented (inter alia Abdi, 2007; O. J. Dunn, 1961; Holm, 1979; Hommel, 1988; Seaman et al., 1991; Simes, 1986). For a comprehensive review see (Holland & Copenhaver, 1988).

The issue is particularly pertinent in scientific disciplines that deal with vast numbers of simultaneous comparisons, for instance, in genetics (e.g., genome-wide association studies, conservation genetics, etc.) (Moskvina & Schmidt, 2008; Narum, 2006). However, even if a researcher tests only two hypotheses, α-error has to be considered, otherwise subsequent logical inferential conclusions might be biased/invalid. To illustrate the general point that statisticians need to explicitly integrate potential sources of error in their analytic efforts Leslie Kish aptly adapted one of Alexander Popes heroic couplets: "*To err is human, to forgive divine but to include errors in your design is statistical.*" (Kish 1978).

Table 38

Hypothesis testing decision matrix in inferential statistics.

Classification of hypothesis-testing decisions		Truth-value of H_0	
		True	**False**
Decision about H_0	**Reject**	α (False Positive) *False interference*	1- α (True Positive) *Correct inference*
	Fail to reject	1- β (True Negative) *Correct inference*	β (False Negative) *False interference*

Note. The Latin-square is isomorphic to the payoff matrix in a legal case, viz., juridical decision-making. The defendant might be guilty or innocent and the judge might decide to sentence the defendant or not.

The appropriate level of significance in relation to the number of comparisons is of direct practical relevance for the research at hand. We conducted a series of experiments (4 of which are reported here) and each experiment consisted of 2 hypothesis tests. *Summa summarum*, this results in a total of 8 hypothesis tests. Because we had specific a *priori* predictions we avoided omnibus *F*-tests, otherwise the number would be even higher. A crucial question is the following: Should one control the experimentwise error rate or the familywise error rate? There are many techniques to correct for multiple comparisons, some of them are statistically more conservative and some are more liberal. If one would apply a simple stepwise Bonferroni correction (experimentwise) to the current analyses, the α-level would be divided by the number of comparisons per experiment. If one applies a classical Bonferroni correction this results in a p-value of 0.05 / 8 = 0.00625. In other words, one should only reject H_0 (i.e., results are only declared as statistically significant) if $p <$ 0.00625. If one would like to control for the familywise error rate the calculation becomes more complex. We will discuss some of the details in the following section.

The familywise error rate defines the probability of making at least one α-error.

FWER $= Pr(V \geq 1)$ where V is the number of α-errors.

Equation 10: Holm's sequential Bonferroni procedure (Holm, 1979).

$$P_{(k)} > \frac{\alpha}{m + 1 - k}$$

The Holm-Bonferroni method ensures that FWER $\leq \alpha$, i.e., it allows the researchers to ensure that the probability of committing one or more α-errors stays below an arbitrary threshold criterion (conventionally α = 0.05 but this decision-threshold can/should be adjusted according to circumstances, e.g., based on a cost-benefit analysis).

- The following example illustrates the procedure:
- Conventional significance level α = 0.05
- smallest P-value: α1 = α/k
- next smallest P-value: α2 = α/(k-1)
- next smallest P-value: α3 = α/(k-2)
- halting-rule: stop at first non-significant α- value

Let $\mathcal{H}_1, \dots, \mathcal{H}_m$ denote a family of hypotheses and $p_1, \dots, p_m$ the *p*-values that were computed after a given experiment has been conducted.

$P_{(1)} \dots P_{(m)}$

1. Significance levels are ordered ascendingly, e.g.:

p-value

0.00001

0.00099

0.00300

0.03500

0.05000

2. The number of tests is quantified:

p-value	*k*
0.00002	1
0.00081	2
0.00337	3
0.03666	4
0.05000	5

3. The number of tests is arranged in an inverse order

p-value	*k*	k^{-1}
0.00002	1	5
0.00081	2	4
0.00337	3	3
0.03666	4	2
0.05000	5	1

4. The respective significance level is divided by the inverse

p-value	*k*	k^{-1}	adjusted *p*-value
0.00002*	1	5	0.05/5=**0.01**
0.00081*	2	4	0.05/4=0.0125
0.00337*	3	3	0.05/3=0.016667
0.03666	4	2	0.05/2=0.025
0.05000	5	1	0.05/1=0.05

5. According to Holm's sequential Bonferroni procedure the first three *p*-values are regarded as significant because they are smaller than the corresponding adjusted *p*-value, i.e., $p <$ adjusted *p*.

Holm's sequential Bonferroni procedure ensures that the family wise error rate (FWER)

$FWER \leq \alpha$

From a statistical point of view, this multiple test procedures is a subclass of so called "closed testing procedures" which entail various methodological approaches for performing multiple hypothesis tests simultaneously.

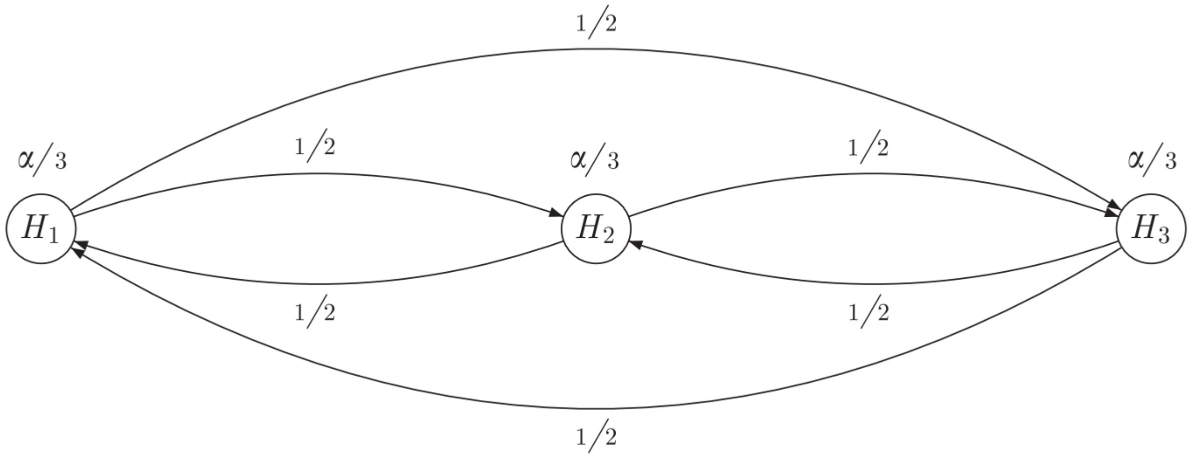

Figure 81. Graphical illustration of the iterative sequential Bonferroni–Holm procedure weighted (adapted from Bretz, Maurer, Brannath, & Posch, 2009, p. 589).

Figure 81 illustrates a Bonferroni-Holm procedure with $m = 3$ hypotheses and an initial allocation of $\alpha = (\alpha/3, \alpha/3, \alpha/3)$. Each node corresponds to an elementary hypothesis and the associative connections are directional and weighted.

Alternative methods for α-control include the Dunn–Šidák correction (Šidák, 1967) and Tukey's honest significance test (Tukey, 1949), *inter alia*. The associated formulae are given below.

Equation 11: Dunn-Šidák correction (Šidák, 1967)

$$\alpha_{SID} = 1 - (1 - \alpha)^{\frac{1}{m}}$$

Equation 12: Tukey's honest significance test (Tukey, 1949)

$$q_s = \frac{Y_A - Y_B}{SE}$$

Interestingly, a recent paper published by Nature (Benjamin et al., 2017) argues for the radical modification of the statistical threshold (in a collective effort numerous authors propose to change the *p*-value to 0.005). We argue that the adjustment of *p*-values for multiple comparisons is at least equally important and it has been shown that researchers generally do not correct for multiple comparisons (Nuijten et al., 2016a). Besides the experimentwise adjustment, the familywise error rate adjustment is even more rarely reported in publications, even though it is at least of equal importance.

Multiple comparisons techniques form an integral part of empirical research. However, they confront researchers with deep philosophical as well as pragmatic problems (Tukey, 1991). Current academic incentive structures put researchers under “enormous pressure to produce statistically significant results” (Frane, 2015, p. 12). It follows that methods that reduces statistical power are not necessarily welcomed by the research community. A recent paper titled “Academic Research in the 21st Century: Maintaining Scientific Integrity in a Climate of Perverse Incentives and Hypercompetition” (Edwards & Roy, 2017) addresses several relevant systemic issue in more detail.

Experimentwise and familywise error control techniques are incongruent with the "publish or perish" (Rawat & Meena, 2014) and "funding or famine" (Tijdink, Verbeke, & Smulders, 2014) mentality imposed on many researchers. If researchers would appropriately utilise statistical methods that substantially reduce α-levels, then they put themselves in a competitive disadvantage (even though the decision to reduce α might be completely rational on logical and statistical grounds). Given that academia is often displayed as a competitive environment, evolutionary principles apply. Academic fitness is closely linked to the number of papers a researcher has published. In an academic climate of hypercompetition, quantitative metrics predominantly determine administrative decision making (Abbott et al., 2010). Specifically, the "track record" of researchers is largely evaluated quantitatively, i.e., researchers are ranked according to the number of publications and the impact factors of the journals they have published in. This leads to publication pressure and the phenomenon of "*p*-hacking" has become a topic of substantial interest in this context (Bruns & Ioannidis, 2016; Head et al., 2015; Veresoglou, 2015). It has been pointed out that the prevailing academic incentive structures implicitly reinforce unethical behaviour and academic misconduct (Edwards & Roy, 2017). In the context of hypothesis testing, the last thing an intrinsically motivated and career-oriented researchers want to learn about are methods that decrease statistical power (independent of the logical foundation of these methods). It is important to recall that hypothesis testing is based on the Popperian logic of falsification. However, it seems as if the logical foundations of hypothesis testing have been almost forgotten. Negative results are almost impossible to publish (Borenstein, Hedges, Higgins, & Rothstein, 2009; Franco, Malhotra, & Simonovits, 2014; Mathew & Charney, 2009; Nuijten et al., 2016b). In order to facilitate the publication of negative result, a special journal was invented: "The Journal in support of the null hypothesis".

However, a single journal cannot counterbalance the publication bias which is associated with the strong emphasis on significant results. Lowering the *p*-value threshold (as has been suggested by a large group of influential researchers (Benjamin et al., 2017; cf. Chawla, 2017))) is therefore also no solution to the "cult of significance testing"[218] . Instead, we need to reconsider the logical fundamentals of the scientific method and how they are implemented in the sociology of science.

Instead of trying to refute their hypotheses, researchers currently largely try to confirm them. This cognitive bias is well-known in the psychology of thinking and reasoning and belongs to the class of "confirmation biases" (M. Jones & Sugden, 2001; Nickerson, 1998; Oswald & Grosjean, 2004), which have been documented in diverse areas, for instance in the context of psychiatric diagnostic decision making (Mendel et al., 2011), financial investments (Park, Konana, & Gu, 2010), and visual search (Rajsic, Wilson, & Pratt, 2015), *inter alia*. However, this (confirmatory) approach towards hypothesis testing stands in sharp contrast with the Popperian logic of hypothesis testing, i.e., falsification. In his books "*The Logic of Scientific Discovery*" (Popper, 1959) and later in "*Conjectures and Refutations: The Growth of Scientific Knowledge*" (Popper, 1962) Popper advocated the concept of "bold hypotheses". According to Popper the growth of scientific knowledge is achieved by means of articulating bold hypotheses (conjectures), and consequently trying to experimentally refute (falsify) them. It is a logical impossibility to conclusively proof a given hypothesis (e.g., all swans are white). Science can only try to falsify (e.g., search for the one black swan in the universe). Hence, researchers should not seek support for their hypotheses, they should try to refute them by all means possible. However, in reality researchers have

[218] The informative book with the fitting title "The cult of significance testing" discusses how significance testing dominates many sciences, i.e., researchers in a broad spectrum of fields, ranging from the zoology, biomedical sciences, to neuroscience, to psychology, etc. pp. employ the *p*-ritual.

vested interest (they are not as objective and neutral as science would demand them to be) and it as has been famously pointed out by Imre Lakatos in his seminal paper titled "*The role of crucial experiments in science*" that in practice scientists try to confirm their hypotheses and do not adhere to falsificationism (Lakatos, 1974).

Falsifiability is a defining demarcation-criterion in Poppers framework which separates "science" from "pseudo-science". A hypothesis which cannot be falsified (e.g., God is love) is not a scientific statement. We argue that null results are at least as important as positive results (if not more so) and we are convinced that editorial policies need to change. Otherwise scientific progress will continue to be seriously impeded. The following parable illustrates the importance of negative results intuitively:

There's this desert prison, see, with an old prisoner, resigned to his life, and a young one just arrived. The young one talks constantly of escape, and, after a few months, he makes a break. He's gone a week, and then he's brought back by the guards. He's half dead, crazy with hunger and thirst. He describes how awful it was to the old prisoner. The endless stretches of sand, no oasis, no signs of life anywhere. The old prisoner listens for a while, then says, Yep, I know. I tried to escape myself twenty years ago. The young prisoner says, You did? Why didn't you tell me, all these months I was planning my escape? Why didn't you let me know it was impossible? And the old prisoner shrugs, and says, So who publishes negative results? (Hudson, 1968, p. 168)

Currently most authors, editors, reviewers and readers are not interested in seeing null results in print. Based on the Popperian logic of falsification[219], null results are important contributions to the corpus of scientific knowledge. The currently prevailing

[219] However, Popper ideas are widely misunderstood and his falsificationism is often reduced to be falsifiability (Holtz & Monnerjahn, 2017). A closer reading of Popper would prevent this misinterpretation.

publication bias (aka. "the file drawer effect" because negative results end up in the file-drawer) is a serious problem which needs to be addressed. Moreover, the proportion of replication studies is minute, that is, almost no published finding is ever replicated as replication is not reinforced. All other statistical considerations (Bayesian vs. frequentists, exact α, correction for multiple comparison, replicability, etc. pp.) are secondary. As long as this fundamental issue is not solved, science cannot call itself rational. Thus far, we have not encountered a single valid argument which justifies the exclusive focus on positive (confirmatory) results.

In addition, the correct adjustment of α-levels is a logical prerequisite for valid inferences and conclusions (that is, in the NHST framework). However, if stringent (appropriate) α-control techniques would be applied, many experiments would not reach statistical significance at the conventional α level (and hence would not get published). This also applies to the "institution-wide error rate"[220], that is the total number of hypotheses which are tested within a given institution over a given period of time. In other words, if researchers within a given institution would apply more conservative criteria, the ranking of the institution would suffer (the ranking is based on research metrics like the total number of publications). It can be seen, that many extraneous illogical factors prevent research from applying proper statistical error correction methods, independent of their logical validity. We term these factors "extralogical factors" in order to emphasise their independence from purely rational scientific considerations. We argue that extralogical factor seriously impede scientific progress

[220] The "institution-wide error rate" is a term invented by the author to refer to the total number of hypotheses tested in a given academic institution. The more hypotheses are tsted, the higher the probability that the institution will publish large numbers of papers which are based on statistically significant results (a key factor for the ranking of the institution and hence for funding). Ergo, institutions might encourage large numbers of studies with multiple hypotheses tests per study in order to gain a competitive advantage in the competition for limited resources (a quasi-Darwinian strategy).

and that they compromise scientific integrity. Furthermore, we argue that interpersonal personality predispositions play an important role in this scenario. Intrinsically motivated researchers focus less on external reinforcement and are more focused on knowledge and accuracy as an inherent intrinsic reward (Sorrentino, Yamaguchi, Kuhl, & Keller, 2008). By contrast, extrinsically motivated researchers are primarily motivated by external rewards. It follows, that under the prevailing reinforcement schedule, intrinsically motivated researchers are in a disadvantaged position, even though their virtuous attitudes are most conducive to scientific progress (Kanfer, 2009; Maslow, 1970). Unfortunately, economic interests dominate academia, a phenomenon Noam Chomsky termed "the corporatization of the university" (Chomsky, 2011) and the ideals of Humboldtian science and education (Hanns Reill, 1994) (e.g., corporate autonomy of universities, holistic academic education) are currently largely supplanted by the military-industrial-entertainment complex (see Chomsky, 2011) and the associated Taylorism (Littler, 1978).

In his analysis "how America's great university system is being destroyed", Chomsky points out that faculty are increasingly hired on the Walmart model" (Punch & Chomsky, 2014). This has obviously implications for the conduct of researchers. If publication metrics are a crucial factor which determines job-security and promotion, then the prevailing incentive contingencies reinforce a focus on self-serving motives which might be incompatible with scientific virtuous which require an altruistic orientation (Edwards & Roy, 2017). The behavioural effects of the prevailing reinforcement contingencies can be largely accounted for in a simple behaviouristic S-R model.

For an extended discussion of this extremely important problem see the article by Henry Steck (2003) entitled "Corporatization of the University: Seeking Conceptual

Clarity" published in "The Annals of the American Academy of Political and Social Science". The article concludes: "To the extent that a corporatized university is no university or corporate values are not academic values … it is the burden for faculty to address the issue of protecting traditional academic values" (p.66). Several insightful books have been published on this topic by Oxford (Ginsberg, 2011) and Harvard (Newfield, 2008) University Press, *inter alia*. The following books provide an in-depth analysis of the situation:

- "Neoliberalism and the global restructuring of knowledge and education" (S. C. Ward, 2012),
- "Global neoliberalism and education and its consequences" (Hill & Kumar, 2009),
- "On Miseducation" (Chomsky & Macedo, 2000)
- "Manufacturing Consent: Noam Chomsky and the Media" (Chomsky, 1992)

Relevant articles include:

- "Educating consent? A conversation with Noam Chomsky on the university and business school education" (P. Fleming & Oswick, 2014)
- "Neoliberalism, higher education and the knowledge economy: From the free market to knowledge capitalism" (Olssen & Peters, 2005)

In this context, we also recommend a review of Edward Bernays' classical work which is important for a basic understanding of mass-psychology (E. L. Bernays, 1928, 1936)[221].

[221] Bernays was a nephew of Sigmund Freund who applied psychoanalytic principles to the public domain (i.e., mass psychology). Bernays is often called the called "the father of public relations" and also "the

This "neo-liberal" shift in academic values and priorities has ramifications for the foundations of science which cannot be underestimated. When universities compete on a "free market" for funding (based on ranking positions) on the basis of the number of publications, α-error control techniques which would limit the output of publications are a topic which is unconsciously or consciously avoided for obvious reasons. For instance "universities have attempted to game the system by redistributing resources or investing in areas that the ranking metrics emphasize" (Edwards & Roy, 2017, p. 54). Related sociological research examined "how and why the practice of ranking universities has become widely defined by national and international organisations as an important instrument of political and economic policy" (Amsler & Bolsmann, 2012).

The reader might question the relevance of this discussion for the research at hand. In anticipation of such an objection we would like to accentuate that these considerations are of practical importance for the calculations of significance levels in the current experiments. Besides, they have real-world implication for the way in which null results are reported (or ignored). Recall the so called "file-drawer effect" (a.k.a. "publication bias") which systematically distorts the validity and reliability of scientific inferences because negative results are not reported in the literature (Asendorpf & Conner, 2012; Borenstein et al., 2009; Kepes, Banks, McDaniel, & Whetzel, 2012; Mathew & Charney, 2009; Møllerand & Jennions, 2001; Jeffrey D. Scargle, 1999; Thornton & Lee, 2000).

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father of spin" (L'Etang, 1999). Bernays was a pioneer in the field of propaganda and he coined the term in his eponymous book (E. L. Bernays, 1928). Propaganda is mainly concerned with what Chomsky calls "the manufacturing of consent" (Chomsky, 1992). The discipline which focuses on mass-psychology (i.e., the systematic manipulation of the masses) was later euphemistically renamed into "public relations" (Ihlen & van Ruler, 2007) after the Nazis "spoiled" the terminus propaganda (Joseph Goebbels was a student of Bernays work).

6.11.6 α-correction for simultaneous statistical inference: familywise error rate vs. per-family error rate

A meta-analysis of more than 30000 published articles indicated that less than 1% applied α-corrections for multiple comparisons even though the median number of hypothesis tests per article was ≈ 9 (Conover, 1973; Derrick & White, 2017; Pratt, 1959). A crucial, yet underappreciated difference, is the distinction between 1) the familywise (or experimentwise) error rate (FWER), and 2) the per-family error rate (PFER). FWER is the probability of making at least one Type I error in a family of hypotheses. The PFER, on the other hand, which is the number α-errors expected to occur in a family of hypotheses (in other words, the sum of the probabilities of α-errors for all the hypotheses in the family).The per-comparison error rate (PCER) is the probability of a α-error in the absence of any correction for multiple comparisons (Benjamini & Hochberg, 1995b). Moreover, the false discovery rate (FDR) quantifies the expected proportion of "discoveries" (rejected null hypotheses) that are false (incorrect rejections).

The majority of investigations focus on the former while the latter is largely ignored even though it evidently is at least equally important if not more so (Barnette & Mclean, 2005; Kemp, 1975). The experimentwise (EW) error rate does not take the possibility of multiple α -errors in the same experiment into account. Per-experiment (PE) α-control techniques control α for all comparisons (*a priori* and *post hoc*) in a given experiment. In other terms, they consider *all* possible α-errors that in a given experiment. It has been persuasively argued that per-experiment α control is most relevant for pairwise hypothesis decision-making (Barnette & Mclean, 2005) even though most textbooks (and researchers) focus on the experimentwise error rate. Both approaches differ significantly in the way they adjust α for multiple hypothesis tests. It has been pointed out that the almost exclusive focus on experimentwise error rates is not justifiable (Barnette & Mclean, 2005). From a pragmatic point of view, per-experiment error correction is much closer aligned with prevailing research practices. In other words, in most experiments it is not just the largest difference between conditions which is of empirical interest and most of the time *all* pairwise comparisons are computed. The EW error rate treats each experiment as one test even though multiple comparisons might have been conducted. A systematic Monte Carlo based comparison between four different adjustment methods showed that, for experimentwise control, Tukey's HSD is the most accurate procedure (as an unprotected test). If experimentwise α-control is desired, Tukey's HSD (unprotected) test is the most accurate procedure. If the focus is on per-experiment α-control, the Dunn-Bonferroni (again unprotected) is the most accurate α-adjustment procedure (Barnette & Mclean, 2005).

6.11.7 Protected versus unprotected pairwise comparisons

In anticipation of the objection why we conducted unprotected comparisons straightway, we will discuss the use of protected vs. unprotected statistical tests in some detail. It is generally regarded as "best practice" to compute *post hoc* pairwise multiple comparisons only after a significant omnibus *F*-test. Many widely sold textbooks either explicitly or implicitly advocate the utilisation of protected tests before post hoc comparisons are conducted (i.a., Kennedy & Bush, 1985; Maxwell & Delaney, 2004). That is, a 2-stage strategy is advocated and widely adopted by most researchers as evidenced in the literature. The 2-stage strategy makes *post hoc* pairwise comparisons conditional on a statistically significant omnibus *F*-test (hence the name protected test). However, this recommendation is not evidence based and there is no analytic or empirical evidence in support of this practice. To the contrary, it has been empirically demonstrated that this strategy results in a significant inflation of α-error rates (Keselman et al., 1979). Further empirical evidence against the 2-stage (protected) testing strategy is based on a Monte Carlo analysis which explicitly compared protected versus unprotected testing procedures. Independent of the error control method used (i.e., Dunn-Šidák, Dunn-Bonferroni, Holm, Tukey's HSD) unprotected tests performed significantly better compared to protected tests (Barnette & Mclean, 2005). This simulation study clearly demonstrated that using the *F*-test as a "protected gateway" for *post hoc* pairwise comparison is overly conservative. The simulation results clearly show that protected tests should not be used. Independent of weather experimentwise or per-experiment α-control is used, and no matter which *α*-error control technique is used (i.e., Dunn-Šidák, Dunn-Bonferroni, Holm, Tukey's HSD, etc.) unprotected tests generally outperformed their protected counterparts.[222] Based on this evidence, it can be safely concluded that unprotected testing procedures should be preferred over 2-stage protected procedures. The conventional wisdom of conducting omnibus tests before *post hoc* comparisons are performed does not stand the empirical/mathematical test. The authors of the previously cited Monte Carlo simulation study conclude their paper with the following statement: "Only when one is willing to question our current practice can one be able to improve on it" (Barnette & Mclean, 2005, p. 452).

6.11.8 Decentralised network systems of trust: Blockchain technology for scientific research

An interesting and innovative proposal is to use blockchain technologies (usually associated with digital crypto currencies like, for instance, Bitcoin or Ethereum) to

[222] A neglectable exception was only the Holm procedure in the case of per-experiment error control (but not in the case of experimentwise error control). In this specific constellation, α of .10 was more accurate as a protected test as compared to an unprotected test. This accuracy difference was lower when α was .05 or .01.

counteract the replication crisis, to validate empirical findings, and to improve and optimize the scientific procedure on a large scale (Bartling & Fecher, 2016). The authors suggest that "Blockchain could strengthen science's verification process, helping to make more research results reproducible, true, and useful" (Bartling & Fecher, 2016, p. 1). Even though this proposal might seem unrealistic or overstated to those unfamiliar with blockchain technologies, we think that this is indeed an excellent innovative and creative proposal because blockchain technologies can be used in all situations which require a high degree of trust. In other words, it is a decentralised (distributed) technology which is useful in many scenarios in which trust is of central concern and it has been predicted that the "blockchain revolution" (Tapscott & Tapscott, 2016a) will influence not only online transactions, but that it will profoundly change many aspects of society which go far beyond financial services (Foroglou & Tsilidou, 2015; Grech & Camilleri, 2017; Idelberger, Governatori, Riveret, & Sartor, 2016; Tapscott & Tapscott, 2016b). Given that the replication crisis challenges the trustworthiness of scientific data, blockchain seems to be a potential candidate which should be carefully considered in this respect. The Economist called the blockchain "the trust machine" (TheEconomist, 2015). Trust "is hardcoded in the Blockchain protocol via a complex cryptographic algorithm" (Benchoufi & Ravaud, 2017). For instance, blockchain-timestamped protocols have been suggested to improve the trustworthiness of medical science (Irving & Holden, 2017). Moreover, the use of blockchain technologies has been suggested to improve clinical research quality where "reproducibility, data sharing, personal data privacy concerns and patient enrolment in clinical trials are huge medical challenges for contemporary clinical research" (Benchoufi & Ravaud, 2017). Based on these proposals and the intrinsic trustworthiness of the implemented cryptographic algorithms, it can be convincingly argued that innovative decentralised blockchain networks might become of central importance to the scientific endeavour. Specifically, it might provide a cryptographic/mathematical basis for transparent, unbiased, and decentralised scientific research of the future. We propose the phrase “the digital decentralisation of science”. An improvement of a part of the system which underlies the scientific method which only became available when sufficient computational resources became available. The decentralised nature of the system is characteristic of a general tendency towards distribution, openness, and transparency. Science and trust are obviously closely interlinked concept. Therefore, science needs to be implemented in an and ideological and technological system which intrinsically support this virtuous feature which lies at the very heart of science. Namely: Trust. In a sense, code is morality, i.e., code defines the laws under which a system operates. The current centralised publishing landscape and the associated editorial policies have all kinds of inherent procedural biases and the selectivity/publications-bias which lies at the core of the replicability crisis is just one of the many manifestations and consequences that impede and compromise the trustworthiness, integrity, and authenticity of the scientific endeavour. Openness and decentralisation is the way forward (Bohannon, 2016; McKenzie, 2017; Perkel, 2016).

6.12 Potential future experiments

6.12.1 Investigating quantum cognition principles across species and taxa: Conceptual cross-validation and scientific consilience

Decision-making is not unique to human primates and has been demonstrated in various animal species (Steven, 2010; A. J. W. Ward, Sumpter, Couzin, Hart, & Krause, 2008), plants (Schmid, 2016), fungi/moulds (Tero et al., 2010), bacteria (Z. Xie, Ulrich, Zhulin, & Alexandre, 2010), viruses (Weitz, Mileyko, Joh, & Voit, 2008), at the cellular level (Perkins & Swain, 2009), and even in single photons (Naruse et al., 2015). Fascinatingly, there appear to exist some astonishing generalities between the decision-making principles that govern these multifarious domains (e.g., Ben-Jacob, Lu, Schultz, & Onuchic, 2014). It would be highly interesting to investigate noncommutativity and constructive principles in completely different domains in order to establish scientific consilience.[223] Are bacterial decisions noncommutative? Are the decisions made by fungal mycelia constructive in nature? Do photobiological processes in various species follow the same principles as human visual perception? If scientific evidence would affirm these research questions this kind of "concordance of evidence" would underline the robustness and generalizability of quantum probability decision-making principles.

Scientific consilience

The strength of evidence increases when multiple sources of evidence converge. This has also been termed the "unity of knowledge" (E. O. Wilson, 1998a). Consilience is based on the utilisation of unrelated research methodologies and measurement

[223] The etymological root of the word consilience is derived from the Latin *consilient*, from *com* "with, together" and *salire* "to leap, to jump," hence it literally means "jumping together" (of knowledge).

techniques. In other words, the research approaches are relatively independent. The generalisability and robustness of converging evidence for a specific logical conclusion is based on the number of different research approaches in support of the conclusion. Furthermore, if equivalent conclusions are reached from multiple perspectives this provides evidence in support of the reliability and validity of the utilised research methodologies themselves. Resilience reduces the impact of confounding factors (e.g., method related measurement errors) because these errors do not influence all research methods equally. Resilience thus "balances-out" method specific confounds. The same principle also applies to logical confounds (e.g., logical fallacies and biases). In the philosophy of science, this has been termed "consilience of inductions" (Fisch, 1985; Hesse, 1968). Inductive consilience can be described as the accordance of multiple inductions drawn from different classes of phenomena. Or, in somewhat more elaborate terms, the "colligation of facts" through "superinduction of conceptions" (Laudan, 1971). The term has recently been adopted by neuroscientists, particularly in the field of neuroeconomics, as exemplified in the SCIENCE paper by (Glimcher, 2004) where the converge of evidence from multiple (hierarchically arrangeable) sources (molecular, cellular, neuroanatomical, cognitive, behavioural, social) plays a crucial role for the development of meta-disciplinary (unifying) theoretical frameworks. Following this line of thought, experiments which would extend quantum cognition principles in domains like bacterial decision-making would be of great value. We propose the term "interdisciplinary polyangulation" (an extension of the concept of methodological triangulation, i.e., compound lexeme consisting of "poly" and "angulation") in order to refer to this kind of transdisciplinary convergence of evidence from diverse scientific disciplines (a neologism created by the author).[224]

6.12.2 Suggestions for future research: Mixed modality experiments

Our experiments focused exclusively on specific sensory modalities (e.g., visual and auditory perception). It would be interesting to investigate our findings in a cross-modal experimental setup to test whether the observed effects are also present in a cross-modal experimental design.

Moreover, it would be important to cross-validate our findings in other sensory modalities like taste and olfaction (the gustatory and the olfactory sense are intimately interlinked). Form a neuroanatomical point of view, olfaction is *sui generis* because it is the only sense which is not relayed through the thalamus (Shepherd, 2005). All other sense signals are relayed through this "integrative hub" (Hwang, Bertolero, Liu, & D'Esposito, 2017) before they reach other cortical areas for further information processing. Therefore, it would be particularly insightful to investigate perceptual noncommutativity and constructive measurement effects in this sensory modality (i.e., for the purpose of neuropsychological dissociation).

[224] According to the Merriam-Webster dictionary, triangulation is defined as "the measurement of the elements necessary to determine the network of triangles into which any part of the earth's surface is divided in surveying; broadly: any similar trigonometric operation for finding a position or location by means of bearings from two fixed points a known distance apart." By contrast to this definition, science is not primarily concerned with the measurement of Cartesian surface areas but with multidimensional conceptual issues which cannot be modelled in 3-dimensional solution space. A multidimensional Hilbert space might be the better visual-metaphor for the problems science is facing. Ergo, the term polyangulation (cf. polymath) is more appropriate than triangulation as it emphasises perspectival multiplicity and the importance of multidisciplinary convergence of multiple sources of evidence. We broadly define the term "interdisciplinary polyangulation" as "a combinatorial interdisciplinary multimethod approach for expanded testing of scientific hypotheses".

6.13 Final remarks

We would like to conclude this thesis with the words of several great thinkers who were enormously influential in the intellectual history of humanity.

"If at first the idea is not absurd, then there is no hope for it."

— Albert Einstein (Hermanns & Einstein, 1983)

"*The instant field of the present is at all times what I call the 'pure' experience. It is only virtually or potentially either object or subject as yet. For the time being, it is plain, unqualified actuality, or existence, a simple that. [...] Just so, I maintain, does a given undivided portion of experience, taken in one context of associates, play the part of the knower, or a state of mind, or "consciousness"; while in a different context the same undivided bit of experience plays the part of a thing known, of an objective 'content.' In a word, in one group it figures as a thought, in another group as a thing. [...] Things and thoughts are not fundamentally heterogeneous; they are made of one and the same stuff, stuff which cannot be defined as such but only experienced; and which one can call, if one wishes, the stuff of experience in general. [...] 'Subjects' knowing 'things' known are 'roles' played, not 'ontological" facts'."*

— William James (James, 1904)

"*My own belief – for which the reasons will appear in subsequent lectures – is that James is right in rejecting consciousness as an entity, and that the American realists are partly right, though not wholly, in considering that both mind and matter are composed of a neutral-stuff which, in isolation is neither mental nor material.*"

— Bertrand Russel (Russel, 1921)

"Even in the state of ignorance, when one sees something, through what instrument should one know That owing to which all this is known? For that instrument of knowledge itself falls under the category of objects. The knower may desire to know not about itself, but about objects. As fire does not burn itself, so the self does not know itself, and the knower can have no knowledge of a thing that is not its object. Therefore through what instrument should one know the knower owing to which this universe is known, and who else should know it? And when to the knower of Brahman who has discriminated the Real from the unreal there remains only the subject, absolute and one without a second, through what instrument, O Maitreyī, should one know that Knower?"

— Jagadguru Śaṅkarācārya

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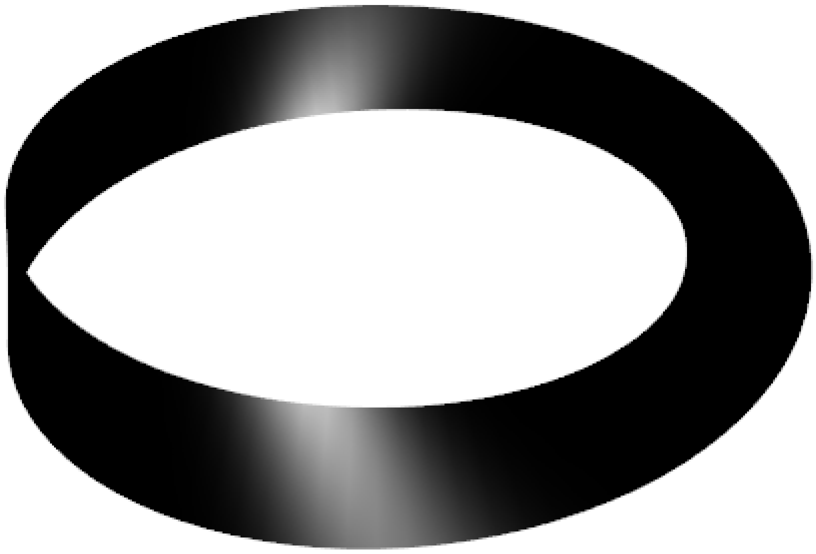
Appendices

Appendix A Introduction

Appendix A1 Möbius band



```
#Source URL: https://r.prevos.net/plotting-mobius-strip/
library(rgl) #RGL: An R Interface to OpenGL (Murdoch, 2001)
library(plot3D) #plot3D: Plotting multi-dimensional data (Soetaert, 2014)
# Define parameters
R <- 3
u <- seq(0, 2 * pi, length.out = 100)
v <- seq(-1, 1, length.out = 100)
m <- mesh(u, v)
u <- m$x
v <- m$y
# Möbius strip parametric equations
x <- (R + v/2 * cos(u /2)) * cos(u)
y <- (R + v/2 * cos(u /2)) * sin(u)
```

```r
z <- v/2 * sin(u / 2)

# Visualise in 3-dimensional Euclidean space

bg3d(color = "white")

surface3d(x, y, z, color= "black")
```

Code 1. R code for plotting an iteractive 3-D visualisation of a Möbius band.

Appendix A2 Orchestrated objective reduction (Orch-OR): The quantum brain hypothesis à la Penrose and Hameroff

The eminent Oxford professor Sir Roger Penrose and anaesthesiologist Stuart Hameroff formulated a neurophysiological model which postulates quantum processes within the neuronal architecture of the brain. Specifically, they hypothesise that the neuronal cytoskeleton isolates microtubule (Conde & Cáceres, 2009) from the environment and forms a protective shield which prevent decoherence from collapsing the extremely fragile quantum processes (through the process of 'Einselection'[225] (Zurek, 2003)). According to the Orch-OR hypothesis, action potentials are generated when superpositional quantum states at the microtubular level collapse. Each cortical dendrite contains microtubule (located at the gap junction) and this creates a network structure of microtubule which can generate a coherent quantum state. The frequency of the microtubular wave function collapse is hypothesised to lie within the EEG spectrum of approximately 40Hz, i.e., within the gamma range (Fitzgibbon, Pope, MacKenzie, Clark, & Willoughby, 2004). The collapse of Ψ within neuronal dendritic-somatic microtubules is thought to be the fundamental basis of consciousness. The frequency of collapse is estimated to occur once every 25ms. Furthermore, the truly interdisciplinary Orch-OR theory "suggests a connection between brain biomolecular processes and fine-scale structure of the universe" (Penrose & Hameroff, 2011, p. 1), i.e., it postulates an intimate relation between neuronal processes and space-time geometry. The theory explicitly raises the question if "the conscious mind [is] subtly linked to a basic level of the universe" (Hameroff, 1998)? A panpsychist perspective (D Chalmers, 2015,

[225] I.e., collapse of Ψ via "environment-induced superselection" (Zurek, 2003). A large proportion of states in the Hilbert space of a given quantum system are rendered unstable (decoherent) due to interactions with the environment (thereby inducing collapse of the wavefunction) since every system is to a certain degree coupled with the energetic state of its environment (entanglement between system and environment).

2016)[226] which is compatible with the Fechnerian psychophysics point of view (because it links the psychological with the physical) and also with the Vedāntic perspective on consciousness (Vaidya & Bilimoria, 2015), as discussed in section 6.1. However, the theory has been severely criticized (e.g., the decoherence problem) and is currently a hotly debated topic (Hameroff & Penrose, 2014c, 2014e, 2014a; Rosa & Faber, 2004; Tegmark, 2000).

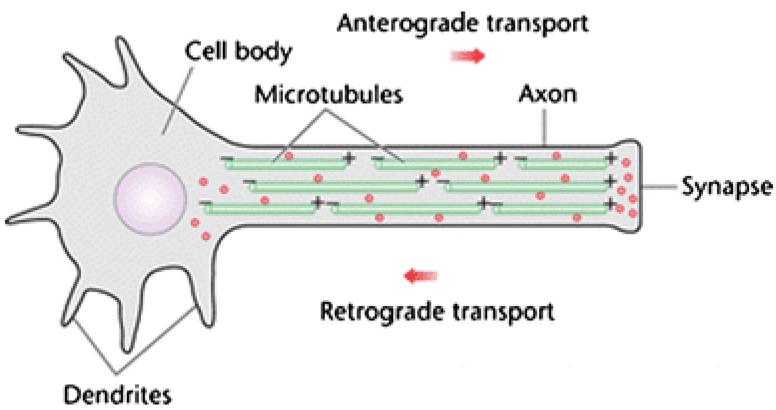


Figure 82. Neuronal microtubules are composed of tubulin. The motor protein kinesin (powered by the hydrolysis of adenosine triphosphate, ATP) plays a central in vesicle transport along the microtubule network (adapted from Stebbings, 2005).

[226] In a Hegelian fashion, Chalmers argues that "the thesis is materialism, the antithesis is dualism, and the
synthesis is panpsychism" (D Chalmers, 2016).

Appendix A3 Algorithmic art to explore epistemological horizons

We alluded to the concept of intrinsic "epistemological limitations" before in the context of the hard problem of consciousness (D. J. Chalmers, 1995). In quantum theory, multidimensional Hilbert space is a crucial concept. However, our cognitive limitations (epistemological boundaries) do currently not allow us to "understand" this concept as no one can visualise more than three dimensions. An evolutionary psychologist would argue that such concepts were not important for our reproduction/survival and therefore such cognitive structures did not evolve (were not selected for) because they did not convey any functional fitness advantage.
In physics, it has been suggested for quite some time that more than four dimensions of spacetime might exists but that these are for some reason imperceptible (Zwiebach, 2009). For instance, in superstring theory spacetime is 10-dimensional, in *M*-theory it is 11-dimensional, and in bosonic string theory spacetime is 26-dimensional.

Art is an extremely valuable tool to expand our concepts of reality and to enhance cognitive flexibility. Artist, futurist, and technologist Don Relyea is a paradigmatic example of an interdisciplinary artist. His artworks combine computer science, logic, and mathematics and provide visual analogies for complex concepts within physics which are oftentimes ineffable. For further digital algorithmic artworks see: http://www.donrelyea.com/

Figure has been removed due to Copyright restrictions

Figure 83. Space filling generative software art installed in Barclays Technology Center Dallas Lobby (November 2014-15).

Figure has been removed due to Copyright restrictions

Figure 84. Algorithmic art: An artistic visual representation of multidimensional Hilbert space (© Don Relyea).

Associated iterative C++ algorithm to create the artistic visual representation of a multidimensional Hilbert space (i.e., infinite dimensional Euclidean space). The algorithm is based on the Hilbert space filling curve:[227]

```
on hilbert_draw(x0, y0, xis, xjs, yis, yjs, n)
–/* n=number of recursions*/
–/* numsteps= number of drawing iterations between two points on the
curve*/
–/* x0 and y0 are coordinates of bottom left corner */
–/* xis & xjs are the i & j components of unit x vector */
–/* similarly yis and yjs */
repeat while n > 0
hilbert_draw(x0, y0, yis/2, yjs/2, xis/2, xjs/2, n-1)
draw_from_to_numsteps( point(x0+xis/2, y0+xjs/2),
point(x0+(xis+yis)/2, y0+(xjs+yjs)/2), numsteps)
hilbert_draw(x0+xis/2, y0+xjs/2 ,xis/2, xjs/2, yis/2, yjs/2, n-1)
draw_from_to_numsteps( point(x0+xis/2, y0+xjs/2),
point(x0+(xis+yis)/2, y0+(xjs+yjs)/2), numsteps)
hilbert_draw(x0+xis/2+yis/2, y0+(xjs/2)+(yjs/2), xis/2, xjs/2,
yis/2, yjs/2,n-1)
draw_from_to_numsteps( point(x0+(xis/2)+(yis/2),
y0+(xjs/2)+(yjs/2)), point(x0+(xis+yis)/2, y0+(xjs+yjs)/2),
numsteps)
hilbert_draw(x0+(xis/2)+yis, y0+(xjs/2)+yjs, -yis/2,-yjs/2, -xis/2,
-xjs/2,n-1)
draw_from_to_numsteps( point(x0+xis/2+yis, y0+xjs/2+yjs),
point(x0+(xis+yis)/2, y0+(xjs+yjs)/2), numsteps)
n=n-1
```

[227] See http://www.donrelyea.com/hilbert_algorithmic_art_menu.htm for further details.

```
if n=0 then exit repeat

end repeat

end
```

Code 2. Algorithmic digital art: C++ algorithm to create a visual representation of multidimensional Hilbert space (© Don Relyea).

Appendix A4 Psilocybin and the HT_{2A} receptor

Psilocybin (*O-phosphoryl-4-hydroxy-N,N-dimethyltryptamine*) is an indole alkaloid which is present in more than 150 fungi species, some of which are endemic to the UK. Its molecular structure closely resembles serotonin (5-hydroxytryptamine, 5-HT). In humans, psilocybin is rapidly dephosphorylated to psilocin (4-N,N-dimethyltryptamine) which functions as a non-selective partial 5-HT receptor agonist and it shows particularly high binding affinity for the 5-HT_{1A} and 5-HT_{2A} receptor subtypes (Carhart-Harris & Nutt, 2017; Nichols, 2004). A landmark study conducted at Johns Hopkins University by MacLean, Johnson & Griffiths (2011) experimentally demonstrated that a single high-dose of psilocybin can induce long-lasting personality changes in the domain "Openness to Experience", as measured by the widely used NEO Personality Inventory. Openness to Experience (OTE) is one of the core dimensions of the extensively employed quinquepartite (big five) model of personality. OTE is an amalgamation of several interconnected personality traits which include: 1) aesthetic appreciation and sensitivity, 2) fantasy and imagination, 3) awareness of feelings in self and others, and 5) intellectual engagement. Most relevant for the context at hand is the fact that OTE has a strong and reliable correlation with creativity (Ivcevic & Brackett, 2015; S. B. Kaufman et al., 2016; Silvia et al., 2009)[228]. Individuals with high scores on the OTE dimension are "permeable to new ideas and experiences" and "motivated to enlarge their experience into novel territory" (DeYoung, Peterson, & Higgins, 2005).

[228] For instance, the Pearson correlation coefficient for "global creativity" and OTE is .655 and for "creative achievement" .481, By contrast, "Math–science creativity" is not statistically significantly correlated with OTE (r =.059; ns; for further correlation between various facets of creativity and the Big Five factors see Silvia, Nusbaum, Berg, Martin, & O'Connor, 2009). The salient correlation between OTE and creativity has been reported in many studies (a pertinent meta-analysis has been conducted by Feist, 1998; a recent study reporting a strong relationship between OTE and creativity has been conducted by Puryear, Kettler, & Rinn, 2017). Furthermore, a meta-analytical structural equation model of 25 independent studies showed that OTE is the strongest FFM predictor of creative self-beliefs (r = .467; Karwowski & Lebuda, 2016).

The experimentally induced increase in OTE was mediated by the intensity of the mystical experience occasioned by psilocybin. Importantly, ego-dissolution is a central feature of mystical experiences (see also Griffiths, Richards, McCann, & Jesse, 2006).

This finding is very intriguing because there is broad scientific consensus that personality traits are relatively stable over time (i.e., a genetic basis is assumed; Bouchard et al., 1990) and can only be altered by major life events (e.g., McCrae & Costa, 1997). Hence, it has been experimentally demonstrated that psilocybin can have profound influences on peoples deeply engrained thinking patterns, emotions, and behaviours. For instance, psilocybin has been very successfully utilised for the treatment of various addictions, major depression and anxiety disorders (for a review see Bogenschutz & Ross, 2016).

Phenomenologically there is a significant degree of similarity between the qualitative experiences induced by psilocybin and those reported by long-term meditators (Griffiths, Richards, Johnson, McCann & Jesse, 2008). Interestingly, the neuronal signature associated with psilocybin shows remarkable overlap with the neuronal activity overserved during mediation (Brewer et al., 2011; cf. Carhart-Harris et al., 2012), i.e., there is convergence between the phenomenology and the neural correlates. Furthermore, mediation has been repeatedly associated with an altruistic orientation (e.g., Wallmark, Safarzadeh, Daukantaitė & Maddux, 2012). A recent multimodal neuroimaging study conducted by Tagliazucchi et al. (2016) conducted at Imperial College London administered LSD intravenously to healthy volunteers. The researchers found that LSD-induced ego-dissolution was statistically significantly correlated with an increase in global functional connectivity density (FCD) between various brain networks (as measured by fMRI). As discussed in the previous study by MacLean et al. (2011), mystical experience is correlated with an increase in OTE which in turn is strongly correlated with creativity. One of the key findings of the current fMRI-study was that high-level cortical regions and the thalamus displayed increased connectivity under the acute influence of LSD. To be specific, increased global activity was observed bilaterally in the high-level association cortices and the thalamus (often regarded as the brains "central information hub" which relays information between various subcortical areas and the cerebral cortices). The global activity increase in the higher-level areas partially overlapped with the default-mode, salience, and frontoparietal attention networks (see Figure 1). The FCD changes in the default-mode and salience network were predicted a priori due their association with self-consciousness. As predicted, a significant correlation between subjective ego-dissolution and activity changes in these networks was detected. That is, the increase in global connectivity was significantly correlated with self-report measures of ego-dissolution.

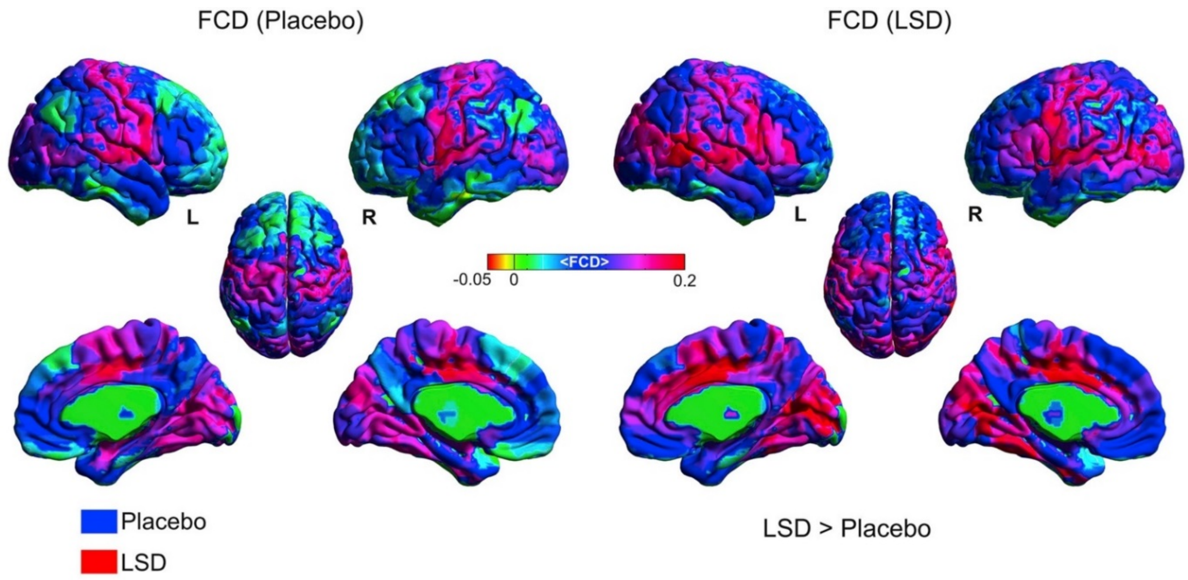


Figure 85. Average functional connectivity density Φ under the experimental vs. control condition (adapted from Tagliazucchi et al., 2016, p. 1044)

The results demonstrate for the first time that LSD increases global inter-module connectivity while at the same time decreasing the integrity of individual modules. The observed changes in activity significantly correlated with the anatomical distribution of

5-HT$_{2A}$ receptors. Interestingly, LSD enhanced the connectivity between normally separated brain networks (as quantified by the widely used Φ connectivity index[229]). This result is especially relevant for researchers who want to identify the neural correlates of creativity because an enhanced communication between previously disconnected neuronal network modules is assumed to be crucial for the generation of novel percepts and ideas (e.g., D. W. Moore et al., 2009). The authors concluded that LSD reorganizes the rich-club architecture of brain networks and that this restructuring is accompanied by a shift of the boundaries between self and environment. That is, the ego-based dichotomy between self and other, subject and object, internal and external, dissolves as a function of specific connectivity changes in the modular networks of the brain[230].

Taken together, Tagliazucchi et al. (2016) demonstrate that LSD induced ego-dissolution is accompanied by significant changes in the neuronal rich-club architecture and that ego-dissolution is accompanied by the downregulation of the default-mode network (DMN). In the context of creativity research this finding is particularly intriguing because the DMN is associated with habitual thought and behavior patterns which are hypothesized to be negatively correlated with creativity and the generation of novel ideas. That is, downregulation of the DMN by psychedelics and the accompanying phenomenology of ego-dissolution are promising factors for the

[229] The rich-club coefficient Φ is a networks metric which quantifies the degree to which well-connected nodes (beyond a certain richness metric) also connect to each other. Hence, the rich-club coefficient can be regarded as a notation which quantifies a certain type of associativity.

[230] Furthermore, the authors argue convincingly that the notion that LSD (and other psychedelics) “expand” consciousness is quantitatively supported by their data. Specifically, they argue that the neurophysiological changes associated with psychedelic states contrast with states of diminished consciousness (e.g., deep sleep or general anesthesia). The obtained results are congruent with the idea that psychedelic and unconscious states can be conceptualized as polar-opposites on a continuous spectrum of conscious states. Furthermore, the authors suggest that the level of consciousness is quantitatively determined by the level of neuronal entropy (in accord with the entropic brain hypothesis formulated by Carhart-Harris et al., 2014). It has been suggested that Aldous Huxley “reduction valve” hypothesis appears to be relevant in this context.

understanding (and enhancement) of creativity.[231] Moreover, the cognitive flexibility which appears to be associated with 5-HT_{2A} agonism (see, for example, Carhart-Harris & Nutt, 2017) is of particular relevance in the context of quantum cognition (and quantum logic in general) because this counterintuitive framework requires a radical reconceptualization (i.e., cognitive restructuring).

[231] Recent evidence focusing on changes in the coupling of electrophysiological brain oscillations by means of transfer entropy suggests that serotonergic psychedelics temporarily change information transfer (via an increase of entropy?) within neural hierarchies by decreasing frontal of top-down control, thereby releasing posterior bottom-up information transfer from inhibition (Francesc Alonso, Romero, Angel Mañanas, & Riba, 2015).

Appendix A5 Gustav Fechner on psychophysical complementarity

Der Mensch lebt auf der Erde nicht *einmal*, sondern *dreimal*. Seine erste Lebensstufe ist ein steter Schlaf, die zweite eine Abwechselung zwischen Schlaf und Wachen, die dritte ein ewiges Wachen.

Auf der ersten Stufe lebt der Mensch einsam im Dunkel; auf der zweiten lebt er gesellig aber gesondert neben und zwischen andern in einem Lichte, das ihm die Oberfläche abspiegelt, auf der dritten verflicht sich sein Leben mit dem von andern Geistern zu einem höhern Leben in dem höchsten Geiste, und schaut er in das Wesen der endlichen Dinge.

Auf der ersten Stufe entwickelt sich der Körper aus dem Keime und erschafft sich seine Werkzeuge für die zweite; auf der zweiten entwickelt sich der Geist aus dem Keime und erschafft sich seine Werk-

Fechner, Büchlein. 6. Aufl. 1

zeuge für die dritte; auf der dritten entwickelt sich der göttliche Keim, der in jedes Menschen Geiste liegt, und schon hier in ein für uns dunkles, für den Geist der dritten Stufe tageshelles, Jenseits durch Ahnung, Glaube, Gefühl und Instinkt des Genius über den Menschen hinausweist.

Der Übergang von der ersten zur zweiten Lebensstufe heißt Geburt; der Übergang von der zweiten zur dritten heißt Tod.

Der Weg, auf dem wir von der zweiten zur dritten Stufe übergehen, ist nicht finstrer als der, auf dem wir von der ersten zur zweiten gelangen. Der eine führt zum äußern, der andere zum innern Schauen der Welt.

"*Man lives on earth not once, but three times: the first stage of his life is continual sleep; the second, sleeping and waking by turns; the third, waking forever. In the first stage man lives in the dark, alone; in the second, he lives associated with, yet separated from, his fellow-men, in a light reflected from the surface of things; in the third, his life, interwoven with the life of other spirits, is a higher life in the Highest of spirits, with the power of looking to the bottom of finite things. In the first stage his body develops itself from its germ, working out organs for the second; in the second stage his mind develops itself from its germ, working out organs for the third ; in the third the divine germ develops itself, which lies hidden in every human mind, to direct him, through instinct, through feeling and believing, to the world beyond, which seems so dark at present, but shall be light as day hereafter. The act of leaving the first stage for the second we call Birth; that of leaving the second for the third, Death. Our way from the second to the third is not darker than our way from the first to the second: one way leads us forth to see the world outwardly; the other, to see it inwardly*."

"On Life after Death" by Gustav Theodor Fechner (1801) translated from the German by Hugo Wernekke.

URL: https://archive.org/stream/onlifeafterdeath00fech#page/30/mode/2up

Appendix A6 Belief bias in syllogistic reasoning

An extensively phenomenon in the psychology of reasoning is termed belief bias (Evans et al., 1983; Markovits & Nantel, 1989). Belief bias labels the long-standing effect that reasoners are more likely to accept a believable conclusion to a syllogism[232] than an unbelievable one, independent of the actual logical validity of the conclusion (i.e. Wilkins, 1928; Henle & Michael, 1956; Kaufman & Goldstein, 1967). For instance, examination of the following syllogism some basic definitions) shows that this argument is logically invalid and that its conclusion does not concord with belief. Consequently, endorsement rates are very low for this type of problem.

Major premise: No police dogs are vicious.

Minor premise: Some highly trained dogs are vicious.

∴Conclusion: Some police dogs are not highly trained.

---

[232] A categorical syllogism (Greek: συλλογισμός svullogisvmìc - conclusion or inference) consists of three parts: the major premise, the minor premise and the conclusion, for example:
Major premise: All animals are mortal.
Minor premise: All humans are animals.
Conclusion: ∴ Ergo, all humans are mortal.
Or in Aristotle's terms: "Whenever three terms are so related to one another that the last is contained in the middle as in a
whole, and the middle is either contained in, or excluded from, the first as in or from the whole, the extremes must be related by a perfect syllogism. I call that term 'middle' which is itself contained in another and contains another in itself."
(Aristotle, Prior Analytics 25b, as cited in Lakoff & Johnson, 1999)

Interestingly, one can construct syllogisms in which validity and believability are discordant, as in the following argument:

Major premise: No addictive things are inexpensive. Minor premise: Some cigarettes are inexpensive. ——————————————— ∴Conclusion: Some addictive things are not cigarettes.

In this example the syllogism is invalid, but the conclusion is believable. Upon inspection, it can be determined that the two exemplary syllogisms have the same logical form. Despite this fact, a major proportion of participants judge the fallacious but believable conclusion as valid, that is, participants exhibit the tendency to judge the validity of a syllogism based on its a priori believability. In their research Evans et al. (1983) reported two main effects, first, participants affirm more believable than unbelievable conclusions and, second, more logically valid than invalid conclusions. Moreover, there was a significant interaction between believability and validity. The effects of belief are stronger on logically invalid than on valid syllogisms. This phenomenon is one of the most prevalent content effects studied in deductive reasoning (for a comprehensive review see Klauer et al., 2000) and it has been demonstrated that response bias to a given syllogism can be influenced by several factors, for example, perceived difficulty of the syllogism (Evans, 2009a), caution (Pollard & Evans, 1980), atmosphere bias (Begg & Denny, 1969), figural bias (Dickstein, 1978; Morley et al., 2004; Jia et al., 2009), presentation order (Lambell et al., 1999), and perceived base rate of valid syllogisms (Klauer et al., 2000), to name just the most prominent factors.

A widely acknowledged descriptive explanation for the belief bias effect is termed the default interventionist (DI) account (see Evans, 2007). Following this account Type 1 and Type 2 processes succeed one another in a sequential order. Primacy is attributed to Type 1 (heuristic) processes which generate a default response whereas recency is ascribed to Type 2 (analytic) processes which approve or override the response generated by Type 1 processes (Stanovich & West, 2000; De Neys, 2006; Evans, 2007; Stanovich, 2008). The process of computing the correct solution and overriding the response cued by Type 1 processes is assumed to be costly in cognitive terms, drawing on limited executive resources. The DI process model is visualized in Figure 86.

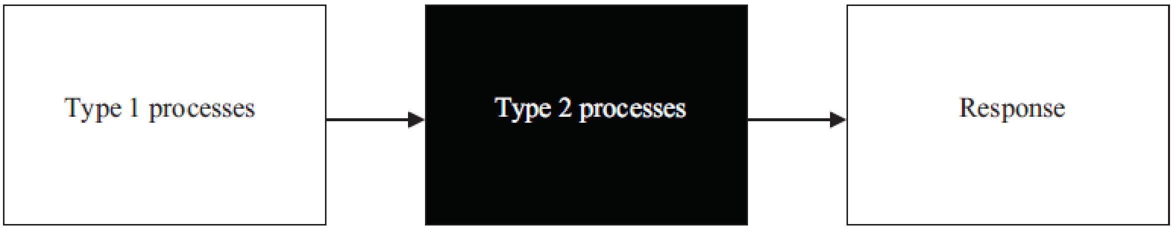


Figure 86. Flowchart depicting the default-interventionist model.

In support of this account, Evans & Curtis-Holmes (2005) showed that rapid responding increases belief bias in a deductive reasoning task. Conceptually related studies indicated that participants with high working memory spans performed better on a reasoning task than those with lower spans when believability of a conclusion conflicted with its logical validity (De Neys, 2006) and that the inhibition of initial responses is related to the capacity of inhibitory processes which covaries with age (De Neys & Franssens, 2009). Further quasi-experimental studies suggest that ecstasy users, due to their reduced working memory capacity, perform worse on syllogistic reasoning tasks than nonusers (Fisk et al., 2005). Other variables that have been related to analytic thinking are, for example, actively open-minded thinking and need for cognition (Kokis et al., 2002). Moreover, recent research suggests that cognitive load has detrimental effects on logical reasoning performance (De Neys, 2006; De Neys & Van Gelder, 2009). In addition, experimental findings summarized by Stanowich (1999) suggest that belief-bias is negatively related to cognitive capacity, that is, individuals low in cognitive capacity are more likely to respond on the basis of belief as compared to logic. It should be empathized that the limited capacity of Type 2 processes is a common theme in much of the cited work. In the context of quantum cognition, it should be emphasised that the empirical scientific facts associated with quantum theory stand in sharp contrast with our prior beliefs about logic and reality in general. Therefore, belief-bias is of great pertinence for the context at hand because it can be predicted that beliefs negatively interfere with logic-based rational argument evaluation (i.e., prior belief bias the logical conclusion in a n irrational manner). Other cognitive biases which are relevant in this respect are confirmation bias (M. Jones & Sugden, 2001; Nickerson, 1998; Oswald & Grosjean, 2004; Rajsic et al., 2015) and asymmetric Bayesian belief updating[233] (Loewenstein & Lerner, 2003; Moutsiana, Charpentier, Garrett, Cohen, & Sharot, 2015; Moutsiana et al., 2013). Both biases account for the human propensity to maintain false beliefs in the face of contradicting evidence. However, a detailed discussion goes beyond the scope of this thesis and we refer the interested reader to the cited literature for further information.

[233] Asymmetric belief updating has also been termed “valence-dependent belief updating” as it refers to “greater belief updating in response to favourable information and reduced belief updating in response to unfavourable information” (Moutsiana et al., 2015, p. 14077)

Appendix A7 Dual-process theories of cognition

Dual-process theories in cognitive psychology hypothesize two qualitatively discernible cognitive processes that operate according to fundamentally different principles. Second-generation cognitive scientists use terms like automatic vs. controlled (Kahneman, 2003), heuristic vs. analytic (Klaczynski, 2001a, 2001b), intuitive vs. reflective (Sperber, 1997), associative vs. rule based (Sloman, 1996), personal vs. subpersonal (Frankish & Evans, 2009), analogue vs. symbolic (Paivio, 1986), reflexive vs. reflective (Lieberman et al., 2002), et cetera. In social psychology dual-process theorists also use a multifarious nomenclature. For instance, heuristic vs. systematic (Chaiken, 1980), peripheral vs. central (Petty & Cacioppo, 1981, 1984), implicit vs. explicit (Greenwald et al., 1998), automatic vs. conscious (Baumeister, 2005), experiential vs. noetic (Strack & Deutsch, 2004), associative vs. propositional (Gawronski & Bodenhausen, 2006), to name just the most popular terms. However, it has been noted that “what matters is not the specific names but the fact of duality” (Baumeister, 2005, p.75). There is remarkable resemblance between dual process models conglomerated in social psychology and those accrued in cognitive psychology. Evans (2009a) criticizes that there have been few attempts to integrate dual-process theories across the different psychological paradigms (for exceptions see E. R. Smith & DeCoster, 2000 or (Barrett et al., 2004)). The now widely used umbrella terms System 1 and System 2 which are used to label the two postulated processes were first introduced by Stanowich (1999). A comprehensive summary of the features attributed to each system has been compiled by Frankish (2009) and is reprinted (in adapted form) in Table 39.

Table 39

Features attributed by various theorists to the hypothesized cognitive systems.

System 1	System 2
Evolutionarily old	Evolutionarily recent
Shared with animals	Uniquely human
Implicit	Explicit
Automatic	Controlled
Parallel	Sequential
Fast	Slow
High capacity	Low capacity
Intuitive	Reflective
Unconscious	Conscious
Contextualized	Abstract
Semantic	Logical
Associative	Rule-based
Not linked to general intelligence	Linked to general intelligence
Independent of executive functions	Dependent on executive functions

Nobel Prize winner Daniel Kahneman is momentarily presumably the most famous dual process theory proponent. During his Nobel Prize lecture[234] he introduced his research project as an "attempt to map departures from rational models and the mechanisms that explain them". Moreover, one of the main points on his agenda was to "introduce a general hypothesis about intuitive thinking, which accounts for many systematic biases that have been observed in human beliefs and decisions" (Kahneman, 2002). He

[234] Associated URL of the official Nobel Prize lecture (2002, Stockholm University): https://www.nobelprize.org/mediaplayer/index.php?id=531

advocates an evolutionary perspective on reasoning and his reflections are based on the assumption that there is a kind of quasi biogenetic progression in the evolution of cognitive processes starting from automatic processes which form the fundamental basis for the evolution of more deliberate modes of information processing. The "phylogenetic" history of higher order cognitive processes could be adumbrated as follows:

PERCEPTION → INTUITION → REASONING

According to this view, perception appears early on the timeline of evolutionary history whereas reasoning evolved relatively recently. Intuition is intermediate between the automatic processes of perception and the deliberate, higher order reasoning processes that are the hallmark of human intelligence (Kahneman, 2003). Furthermore, he proposes that intuition is in many ways similar to perception and the analogy between perception and intuition is the common denominator of much of his work. Perception is a highly selective process which focuses on certain characteristics of the environment neglecting others. One could argue that reality is a continuous multimodal attack on our senses. The perceptual system deals with this in different ways. For example, we perceive discrete events (Tversky et al., 2008) and exclude irrelevant features from perception (Lavie et al., 2004; Simons & Chabris, 1999) whereas other features "pop-out" due to their salience (Treisman & Gelade, 1980). Moreover, some features are directly available to perception whereas other features are not. Kahneman argues that most of the time we do not engage in effortful thinking and reasoning. Our standard mode of operations is intuitive thinking. This is the fundamental assumption underlying the two-system view, which differentiates between intuition and reasoning. In the context of dual process theories of reasoning Kahneman (2003) argues that System 1 processes are responsible for repeating simple and automatic operations, whereas

System 2 processes are accountable for deliberate mental operations and the detection and correction of errors made by System 1. In order to illustrate the dual-system approach we would like the reader to answer the following question (adapted from Frederick, 2005):

A BAG AND A BOOK COST TOGETHER £110.

THE BAG COST £100 MORE THAN THE BOOK.

WHAT DOES THE BOOK COST?

For most people the first thing that comes to mind is £10. Of course, this answer is incorrect. Using the terminology of dual-process theories, System 1 has produced a fast heuristic response and the slower System 2 is able to scrutinize this response analytically and might eventually correct it. This example neatly demonstrates the heuristic vs. analytic distinction in dual-process theory (Evans, 2006; Kahneman, 2003; Klaczynski, 2001b). Sloman (2002) also supports the notion of two different systems of reasoning and proclaims that people can believe in two contradictory responses simultaneously. Sloman articulates that "the systems have different goals and are specialists at different kinds of problems" (Sloman, 1996, p.6). In order to elucidate his argumentative line he uses an example of a judge (Sloman, 2002). Judges often have to neglect their personal beliefs and decide a given case on the basis of evidence according to the law. It is thus possible that the belief-based response of the judge continues to be compelling regardless of certainty in the second response based on the juridical law. In addition, Sloman (2002) employs the classical Müller-Lyer illusion (Müller-Lyer, 1889) in order to illustrate that two independent systems are at work (see Figure 87).

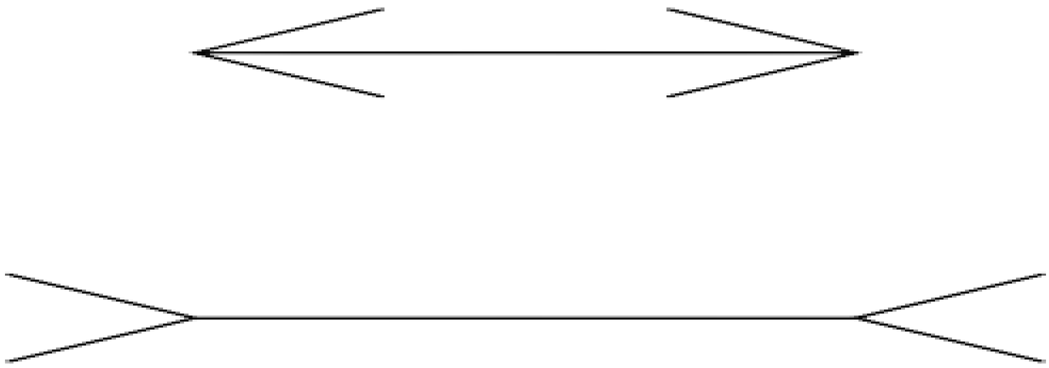


Figure 87. The Müller-Lyer illusion (Müller-Lyer, 1889).

Even when the percipient knows that the two lines are of equal length the two lines are still perceived as different. In other words, explicit knowledge (System 2) about physical reality does not alter the visual percept (System 1). This classical example provides anecdotal evidence for the existence of two cognitive systems, because people can believe in two contrary responses simultaneously. A rich body of research demonstrates that the balance between these two stipulated types of thinking can be shifted. Methods for shifting the balance to System 1 processes involve concurrent working memory load (Gilbert, 1991) in order to interfere with System 2 processes and the use of time pressure (Finucane et al., 2000) to impose temporal processing constrains on System 2. Moreover, System 2 processing can be facilitated by explicitly instructing people to employ logical reasoning (Klauer et al., 2000). In addition, there are dispositional factors which are correlated with the functioning of System 2, for instance, individual differences variables like the extensively studied "need for cognition" (Shafir & LeBoeuf, 2002) and general cognitive ability (Stanovich & West, 1998, 2000). In addition, individual differences in executive functioning, working-memory capacity, and self-control appear to play a pivotal role in this context. From a neuroscientific point of view, the prefrontal cortices (PFC) are assumed to be responsible for executive control of different tasks (Miller & Cohen, 2001). However, precise localization of function is difficult because the brain is a complex and integrated system. Many researchers argue against a fully modular and departmentalized anatomical view and for a continuous view on psychological constructs and processes (but see Stuss, 1992). It has been noted that, "it is entirely possible that, although the frontal lobes are often involved in many executive processes, other parts of the brain may also be involved in executive control" (Baddeley, 1996, p. 6-7; see also Braver et al., 1997). However, it seems as if certain brain regions are more involved in executive functioning than others and the prefrontal cortices have been associated with executive control function (Della Sala et al., 1998), supervisory system (Shallice, 2001; Alexander et al., 2007), and dysexecutive syndrome (Baddeley & Wilson, 1988; Laine et al., 2009). Three regions seem to be particularly involved in executive functioning, working memory, and self-control: 1) the dorsolateral prefrontal cortex (DL-PFC) 2) the ventromedial prefrontal cortex (vmPFC) and 3) the and the anterior cingulate cortex (ACC) (see Figure 88).

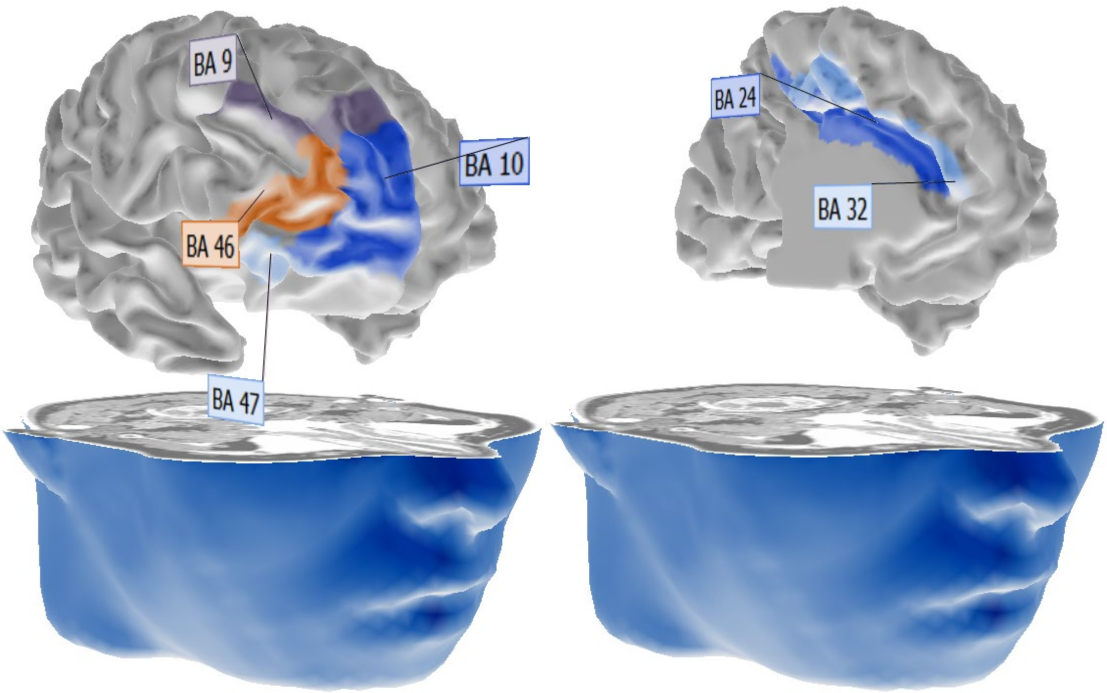


Figure 88. Neuroanatomical correlates of executive functions (DL-PFC, vmPFC, and ACC)

Left picture: Dorsolateral prefrontal cortex (Brodmann area 46 and 9), ventromedial prefrontal cortex (BA10) and inferior prefrontal gyrus (BA47). Right picture: ventral (BA24) and dorsal (BA32) anterior cingulate cortex. 3D graphics were created using the “BrainVoyager” software package (Goebel, 2007).

Space does not permit a detailed discussion of these neuroanatomical structures which appear to be crucial for sound logical reasoning and the inhibition of (habitual/automatic) belief-based responses. However, we will briefly outline some of the main characteristics in the following paragraphs (we refer the interested reader to Miller & Cohen, 2001). For instance, Fuster (1997) argued that the DL-PFC houses working memory whereas the ventral-prefrontal cortex is associated with inhibition of (automatic) behavioural responses. However, other researchers (e.g., May et al., 1999) disagreed, claiming that this functional dichotomy is not evident because the processes are concatenated and dependent on one another. It has been suggested that the dorsolateral prefrontal cortex is associated with the implementation of cognitive control, executive functioning, working memory, attentional switching and selective attention, whereas the ventromedial prefrontal cortex is assumed to moderate amygdala activity, that is, emotions and emotional reactions (Bechara et al., 1999; Duncan & Owen, 2000). The anterior cingulate cortex is assumed to be involved in performance monitoring and detection of conflict and selection of appropriate responses (MacDonald et al., 2000; Miller & Cohen, 2001; Pochon et al., 2008; Posner & Rothbart, 2009). Based on imaging data and lesion studies researchers concluded that especially the dorsal ACC is very likely involved in situations that involve decision making, conflict, and inhibition (Ochsner & Gross, 2004, p.236). Moreover, it has been suggested that self-control and executive functions are both associated with an increase in anterior cingulate cortex activity (but see Posner et al., 2007).

Appendix A7 Bistability as a visual metaphor for paradigm shifts

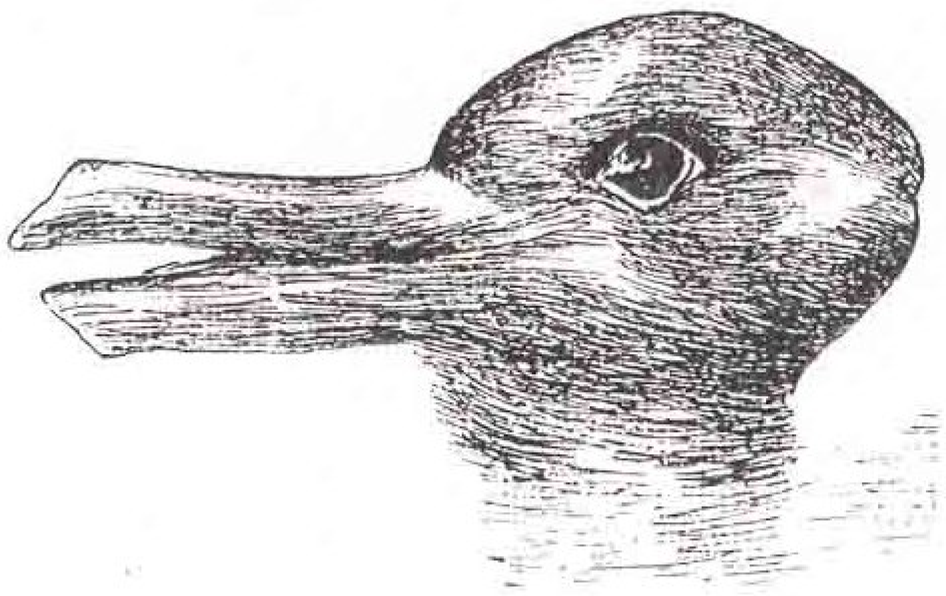


Figure 89. Bistable visual stimulus used by Thomas Kuhn in order to illustrate the concept of a paradigm-shift.

Thomas Kuhn used the duck-rabbit (Brugger, 1999) to illustrate the fundamental perceptual change that accompanies a scientific paradigm-shift. The concept of incommensurability is pertinent in this context, i.e., the impossibility of direct comparison of complementary theories. It is impossible to see both percepts simultaneously (it is either a rabbit or a duck – the ambiguous superposition of both cannot be perceived by the visual system). In the same way, it is impossible to entertain conflicting scientific paradigms simultaneously. The human cognitive system automatically reduces ambiguity and thrives for closure (Webster & Kruglanski, 1994). In contemporary psychology, bistable perception is a topic of ongoing research (Sterzer & Rees, 2010). Recently, it has been investigated in the theoretical framework of quantum cognition, i.e., with respect to the complementarity principle and the quantum-zeno effect (Atmanspacher & Filk, 2010, 2013, Atmanspacher et al., 2004, 2009). Harald Atmanpachers' creative idea was to treat the underpinning process of bistable perception in terms of the evolution of an unstable two-state quantum system. In quantum physics, the quantum Zeno effect is a situation in which an unstable particle, if observed continuously, will never decay. To be precise, "The coupling of an unstable quantum system with a measuring apparatus alters the dynamical properties of the former, in particular, its decay law. The decay is usually slowed down and can even be completely halted by a very tight monitoring." (Asher Peres, 1980)

The Zeno effect is also known as the Touring paradox:

"*It is easy to show using standard theory that if a system starts in an eigenstate of some observable, and measurements are made of that observable N times a second, then, even if the state is not a stationary one, the probability that the system will be in the same state after, say, one second, tends to one as N tends to infinity; that is, that continual observations will prevent motion …*"

— Alan Turing as quoted by A. Hodges in Alan Turing: Life and Legacy of a Great Thinker p. 54

Appendix A8 CogNovo NHST survey: A brief synopsis

"Few researchers are aware that their own heroes rejected what they practice routinely. Awareness of the origins of the ritual and of its rejection could cause a virulent cognitive dissonance, in addition to dissonance with editors, reviewers, and dear colleagues. Suppression of conflicts and contradicting information is in the very nature of this social ritual." (G Gigerenzer, 2004, p. 592)

Null hypothesis significance testing (NHST) is one of the most widely used inferential statistical techniques used in science. However, the conditional syllogistic logic which underlies NHST is often poorly understood by researchers. That is, researchers using NHST often misinterpret the results of their statistical analyses. Fallacious scientific reasoning is a problem with huge ramifications. If researchers regularly misinterpret the meaning of p-values this implies that the conclusions, they derive from their research are often logically invalid. How often is an empirical question which is worth investigating in more detail.

This paper briefly describes the results of a small-scale survey we conducted at the interdisciplinary "CogNovo Research Methods Workshop" at Plymouth University in June 2014. Participants were Phd students, research fellows, lecturers, and professors who attended the workshop with the adequate title "The Pitfalls of Hypothesis Testing". At the very beginning attendees were asked to interpret the results of the following simple independent means *t* test.

Participants were asked to mark each of the statements below as "True" or "False" (adapted from Oakes, 1986).

Suppose you have a treatment which you suspect may alter performance on a certain task. You compare the means of your control and experimental group (say 20 subjects in each sample). Further, suppose you use a simple independent means *t* test and your result is ($t = 2.7$, *d.f.* 18, $p = 0.01$).Please mark each of the statements below as "True" or "False".

Statement1
You have absolutely disproved the null hypothesis (that is, there is no difference between the population means).

- ○ True
- ○ False

Statement2
You have found the probability of the null hypothesis being true.

- ○ True
- ○ False

Statement3
You have absolutely proved your experimental hypothesis (that there is a difference between the population means).

- ○ True
- ○ False

Statement4
You can deduce the probability of the experimental hypothesis being true.

- ○ True
- ○ False

Statement5
You know, if you decide to reject the null hypothesis, the probability that you are making the wrong decision.

- ○ True
- ○ False

Statement6
You have a reliable experimental finding in the sense that if, hypothetically, the experiment were repeated a great number of times, you would obtain a significant result on 99% of occasions.

- ○ True
- ○ False

Submit

Adapted from Oakes, M. (1986). *Statistical inference: A commentary for the social and behavioral sciences*. New York: Wiley.

The *t* test at hand is a very basic exemplar of the kind of significance testing which many scientists routinely employ. Hence, its correct interpretation is of paramount importance for many far-reaching real-world decisions and the progress of science in general.

In our experiment we utilized a custom-made web-based questionnaire in order to collect the responses from participants. The HTML code utilised responsive web-design CSS -techniques which allowed participants to visit the website immediately (during the lecture) on various devices with varying resolution (laptops, tablets, smart-phones, ect.). We asked only those workshop attendees who had prior experience with statistical significance testing to participate. A total of 18 participants responded to each of the 6 statements within ≈ 5minutes by using their mobile phones, notebooks, or tablets. The resulting data-set is available under the following URL:

https://docs.google.com/spreadsheets/d/1qEcJGoCBMDCXNbkttgZirWJzNJRqyxFEmHzk8hToZhk/edit?usp=drive_web#gid=0

The lecture itself is available on YouTube under the following URL:

https://youtu.be/wOYgQzCLiBQ?t=1939

The powerpoint slides used in this presentation can be downloaded as a PDF.

http://irrational-decisions.com/hypothesis-testing%20-full-web-version.pdf
(password: cognovo)

We analysed the data in real-time during the presentation of the talk using the following custom-made R code which utilises the RCurl package (Lang, 2006) to pull the data from the server.

```
#library(RCurl)
#install.packages("RCurl", contrib.url="http://cran.rstudio.co
m")
#download data from server
api = function(key,query,gid=0){tmp=getURL(paste(
 sep="",'https://spreadsheets.google.com/tq?',
 'tqx=out:csv',
 '&tq=',curlEscape(query),
 '&key=',key,'&gid=',gid),
 ssl.verifypeer=FALSE)
 return(read.csv(textConnection(tmp)))
}
#key for spreadsheet
p=api('0ArGYdGO1obvSdEs5dnYtM1BuckhhMHdmNDVDZkIxT2c',
'select * order by F limit 100')
#write summary
summary(p)
#recode
yes = c()
no = c()
for(i in 1:6){
  yes[i] = sum(p[,i])
  no[i] = length(p[,i]) - sum(p[,i])
}
#plot data
barplot(rbind(yes,no),
        beside=FALSE,
        main="Frequencies of TRUE and FALSE responses",
        xlab="Statement",
        ylab="Number of responces",
        legend.text = c("TRUE", "FALSE"),
        args.legend = list(x = "topright", bty = "n", inset=c(
-0.05, -0.15)),
        names.arg=c("#1","#2","#3","#4", "#5", "#6"),
        col=c("green","red")
)
```

Altogether, only one participant responded correctly to all statements. The remaining 17 participants indicated that at least 1 of the 6 statements would be correct. Note that the p-value is the probability of the observed data (or of more extreme data points), given that the null hypothesis H_0 is true, defined in symbols as $p(D|H_0)$. The results of the survey are visualized in Figure 1.

Logical fallacies in interpretation

The following paragraphs will deconstruct the logical fallacies committed by the majority of participants (see Cohen, 1994, 1995, G Gigerenzer, 1993, 1998, 2004).

Statements 1 and 3 are easily detected as logically invalid. A significance test can never prove or disprove the null hypothesis or the experimental hypothesis with certainty. Statement 1 and 3 are instances of the epistemological illusion of certainty (G Gigerenzer & Krauss, 2004). As can be seen in Figure 1, all participants gave the correct response to statement 1, however, 2 participants believed that statement 2 is true.

Statements 2 and 4 are also false. The probability $p(D|H_0)$ is not the same as $p(H_0|D)$, and more generally, a significance test does *never* provide a probability for a hypothesis. To equate the direct probability with its inverse is an illusionary quasi-Bayesian interpretation of $p(D|H_0)$. This has been termed *the inverse problem*.

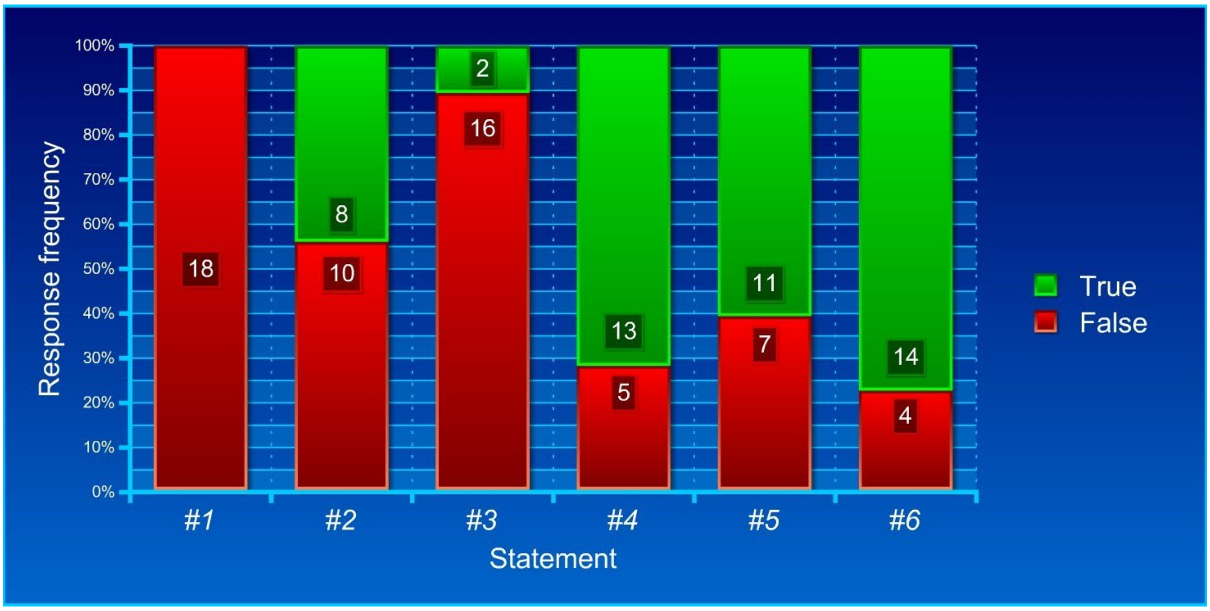


Figure 90. Results of CogNovo NHST survey

Equation 13. The inverse probability problem

$$\mathbf{p(D|H_0) \neq p(H_0|D)}$$

This particular illusion has been perpetuated by many statistics textbooks (for further examples see Gigerenzer, 2000). For instance, in one of the early texts "Guilfords' Fundamental Statistics in Psychology and Education" the *p* values turns miraculously into a Bayesian posterior probability:

“If the result comes out one way, the hypothesis is probably correct, if it comes out another way, the hypothesis is probably wrong” (p. 156). Guilford is no exception. He signifies the beginning of a class of statistical texts that presents significance testing as a hybrid between Fisherian and Neyman/Pearsonian methods without mentioning its origins (Gigerenzer 2000 terms this “the denial of parents”). Neither Fisher or Neyman/Pearson would have agreed upon the hybrid method because they disagreed vehemently. The currently used hybrid additionally confuses the researchers’ desire for probabilities of hypotheses and what significance testing can actually provide (that is, a Baysian interpretation is added to the already incompatible combination).

Statement 5 also refers to a probability of a hypothesis. This is because if one rejects the null hypothesis, the only possibility of making a wrong decision is if the null hypothesis is true. Thus, it makes essentially the same claim as Statement 2 and 4 do, and both are incorrect.

Statement 6 amounts to the *replication fallacy* (Gigerenzer, 1993, 2000). Here, p=1% is taken to imply that such significant data would reappear in 99% of the repetitions.

However: **$p(D|H_0)$ does not entail any information about *p*(replication)**

Especially the replication fallacy seems to be widespread. For example, the editor of the top-ranking *Journal of Experimental Psychology* stated that he used the level of statistical significance reported in submitted papers as the measure of the “confidence that the results of the experiment would be repeatable under the conditions described” (Melton, 1962, p. 553). Contrary to his belief, the p-value conveys no information at all about the replicability of an experimental finding.

Logical inconsistency between responses

Statement 2, 4, and 5 are logical implications of one another. To be logically consistent all three statements should either be rejected or approved.

- 8 participants were inconsistent when responding to statement 2, 4, and 5.

- 3 participants described all three statements correctly as false.
- 7 (although wrongly) described all three statements as true.

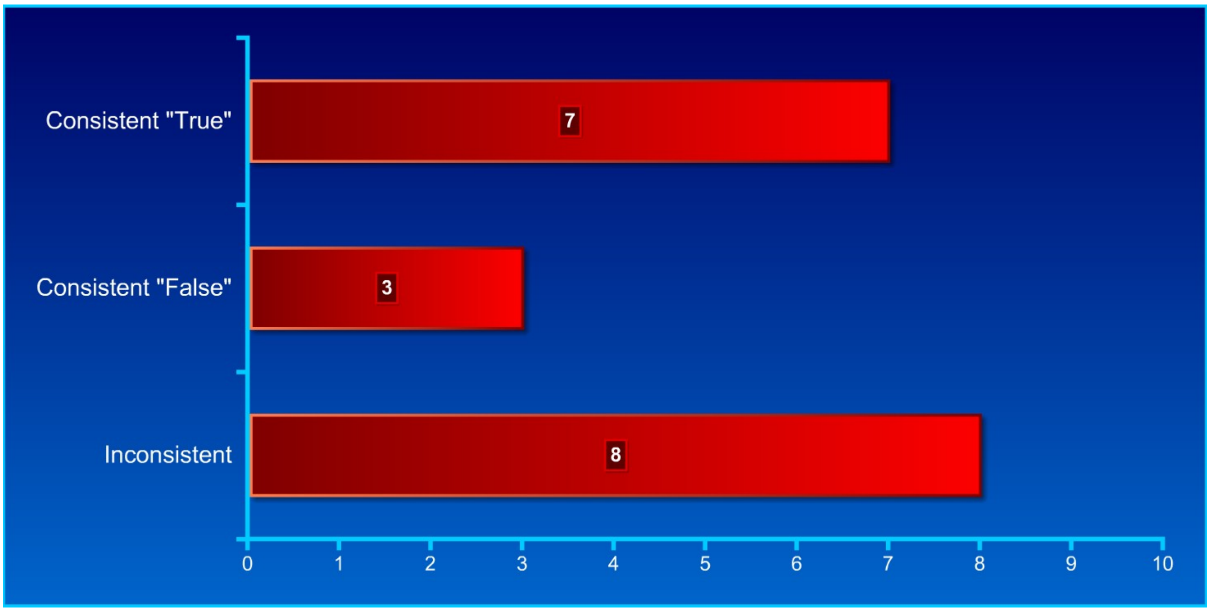


Figure 91. Logical consistency rates

International comparison with other universities

Table 40.

Comparison between international universities and between academic groups.

	Plymouth University (UK)	**Psychological Departments German Universities**			**USA (Oakes, 1986)**
	Current experiment	Methodology Instructors	Scientific Psychologists	Psychology Students	Academic Psychologists
#1)	0%	10%	15%	34%	1%
#2)	44%	17%	26%	32%	36%
#3)	11%	10%	13%	20%	6%
#4)	61%	33%	33%	59%	66%

#5)	72%	73%	67%	68%	86%
#6)	77%	37%	49%	41%	60%

Overall, statement 1, 2, and 3 are more often correctly falsified as compared to statement 4, 5, and 6.

Table 41

Fallacious NHST endorsement rates per group.

Professors and lecturers teaching statistics (N=30):	80%
Professors and lecturers (N=39):	90%
Students (N=44):	100%

Table 2. The amount of wrong interpretations of p = 0.01. The table shows the percentage in each group who endorsed one or more of the six false statements (Haller & Krauss, 2002).

Brief discussion

The results of this investigation have serious implications because they demonstrate that the misinterpretation of NHST is still a ubiquitous phenomenon among researchers in different fields, despite the fact that this issue has been strenuously pointed out repeatedly before (Rozeboom , 1960; Meehl, 1978; Loftus, 1991; Simon, 1992; Gigerenezer, 1993; Cohen, 1994). We argue that wishful Bayesian thinking (made possible by fallaciously mistaking direct probabilities for inverse probabilities) lies at the core of these pertinacious cognitive illusions. Unfortunately, far reaching real world decisions are based on the conclusions drawn from these demonstrably widely misunderstood test procedures.Therefore, educational curricula should make sure that students understand the logic of null hypothesis significance testing.

The syllogistic logic of NHST

From a logical point of view NHST is based upon the logic of conditional syllogistic reasoning (Cohen, 1994). Compare the following syllogisms of the form *modus ponens*:

Syllogism 1

1st Premise:

If the null hypothesis is true, then this data (D) can not occur.

2nd Premise:

D has occurred.

Conclusion:

∴ H_0 is false.

If this were the kind of reasoning used in NHST then it would be logically correct. In the Aristotelian sense, the conclusion is logically valid because it is based on deductive proof (in this case denying the antecedent by denying the consequent). However, this is not the logic behind NHST. By contrast, NHST uses hypothetical syllogistic reasoning (based on probabilisties), as follows:

Syllogism 2

1st Premise:

If H_0 is true, then this data (D) is highly unlikely.

2nd Premise:

D has occurred.

Conclusion:

$\therefore H_0$ is highly unlikely.

By making the major premise probabilistic (as oposed to absolute, cf. Syllogism 1) the syllogism becomes formally incorect and consequently leads to an invalid conclusion. The following structure of syllogistic reasoning is implicitly used by many authors in uncountable published scientific articles. This logical fallacy has been termed the "the illusion of attaining improbability". (Cohen, 1994, p.998).

Syllogism 3

1st Premise:

If H_0 is true, then this data (D) is highly unlikely.

2nd Premise: D

has occurred.

Conclusion:

$\therefore$ H_0 is probably false.

Note: $\mathbf{p(D|H_0) \neq p(H_0|D)}$

Belief bias and wishful thinking in scientific reasoning

Most importantly, all fallacious interpretations are unidirectional biased: they make the informational value of p appear bigger than it in reality is. In other words, researchers are positively biased with regards to the interpretation of *p*-values because they attribute more informational value to the *p*-value than it actually contains.

Cohen (1994, p.997) formulated the problem very clearly: "What's wrong with significance testing? Well, among many other things, it does not tell us what we want to know, and we so much want to know what we want to know that, out of desperation, we nevertheless believe in that it does! What we want to know is 'given these data, what is the probability that H_0 is true?

But as most of us know, what it tells us is *given that H_0 is true, what is the probability of these or more extreme data*." (italics added)

Moreover, Gigerenzer (2000) clearly agrees with Cohen (1984) that the currently used hybrid logic of significance testing is "A mishmash of Fisher and Neyman-Pearson, with invalid Bayesian interpretation" (Cohen, 1994, p. 998). The historical genesis of the hybrid is very revealing. An eye-opening historical perspective on the widely unacknowledged but fierce debate between Fisher and Neyman/Pearson is provided by Gigerenzer (1987).

Broader implications

Given that inferential statistics are at the very heart of scientific reasoning it is essential that researchers have a firm understanding of the actual informative value which can be derived from the inferential techniques they employ in order to be able to draw valid conclusions. Future studies with academicians and PhD students from different disciplines are needed to determine the epidemiology[235] of these statistical illusions. The next step would be to develop and study possible interventions (but see Lecoutre et al., 2003).
We suggest that is necessary to development novel pedagogical concepts and curricula in order to teach the logic of NHST to students. Moreover alternative statistical inferential methods should be taught to students given that there is no "magic bullet" or "best" inferential method per se. Gigerenzer (1993) points out that "it is our duty to inform our students about the many good roads to statistical inference that exist, and to teach them how to use informed judgment to decide which one to follow for a particular problem" (p. 335). We strongly agree with this proposition.

Pertinent citations from eminent psychologists

[235] Epidemiology literally means "the study of what is upon the people"and the term is derived from Greek epi, meaning "upon, among", demos, meaning "people, district", and logos, meaning "study, word, discourse". In that sense, the current investigation can be regarded as an ethnographgic studie.

"I suggest to you that Sir Ronald has befuddled us, mesmerized us, and led us down the primrose path. I believe that the almost universal reliance on merely refuting the null hypothesis is one of the worst things that ever happened in the history of psychology." (Meehl, 1978, p. 817; Former President of the American Psychological Association, *inter alia*)

The eminent and highly influential statistician Jacob Cohen argues that null hypothesis significance testing *„not only fails to support the advance of psychology as a science but also has seriously impeded it."* (Cohen, 1997, p. 997; * 1923; † 1998; Fellow of the American Association for the Advancement of Science, *inter alia*)

"Few researchers are aware that their own heroes rejected what they practice routinely. Awareness of the origins of the ritual and of its rejection could cause a virulent cognitive dissonance, in addition to dissonance with editors, reviewers, and dear colleagues. Suppression of conflicts and contradicting information is in the very nature of this social ritual." (Gigerenzer, 2004, p. 592; Director Emeritus of the Center for Adaptive Behavior and Cognition at the Max Planck Institute for Human Development, *inter alia*)

Appendix A9 Reanalysis of the NHST results reported by White et al. (2014) in a Bayesian framework

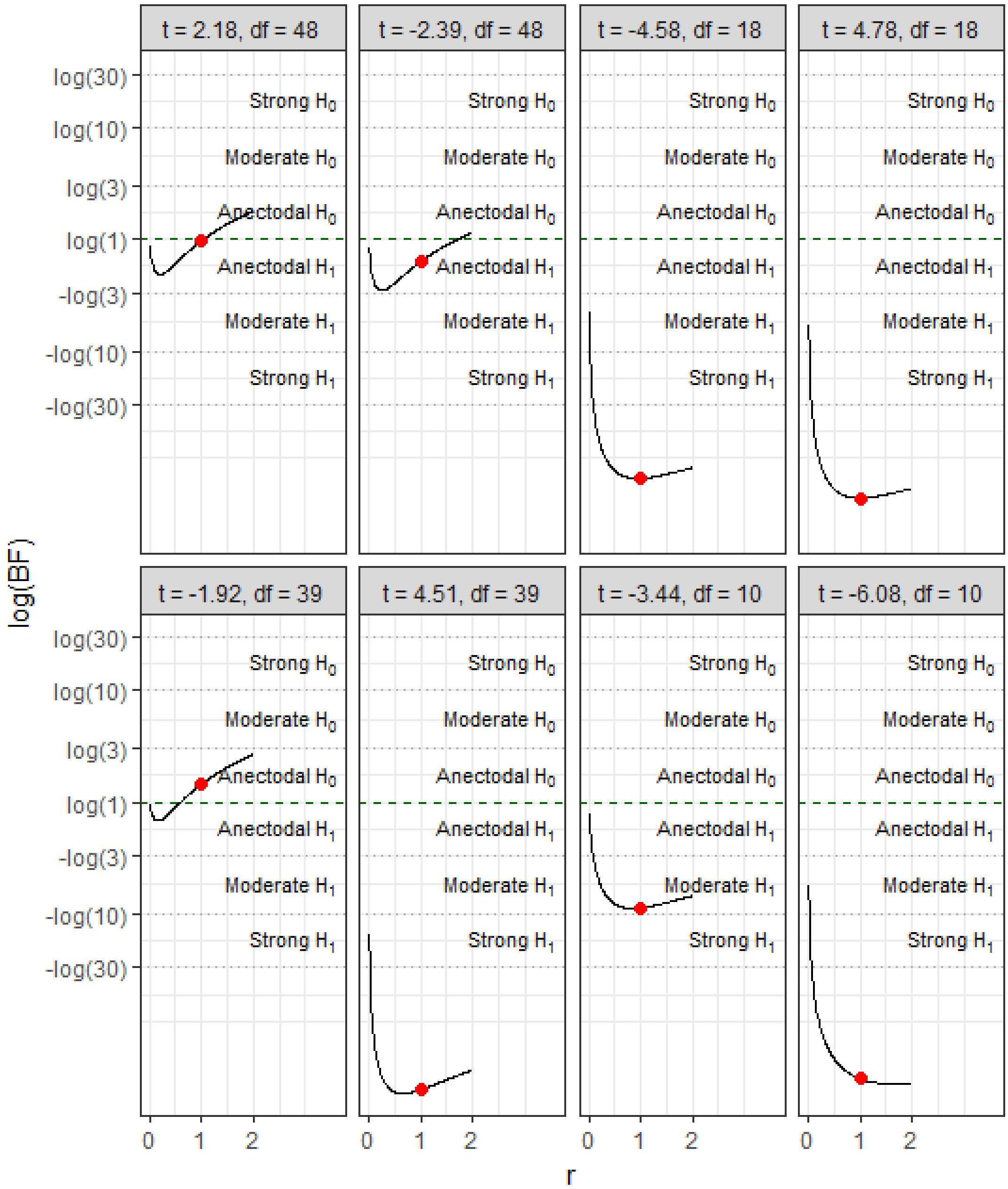


Figure 92. Bayesian reanalysis of the results NHST reported by White et al., 2014.

Note that the results are not entirely congruent the with conclusions drawn from the NHST analysis. The associated R code which utilises the "`BayesFactor`" package (R D. Morey & Rouder, 2015) is appended below.

```
## This source code is licensed under the FreeBSD license
## (c) 2013 Felix Schönbrodt
# Morey, R. D., Rouder, J. N., & Jamil, T. (2014). BayesFactor: Computation
of Bayes factors for common designs. R Package Version 0.9, 8.
install.packages("BayesFactor")

#' @title Plots a comparison of a sequence of priors for t test Bayes
factors
#'
#' @details
#'
#'
#' @param ts A vector of t values
#' @param ns A vector of corresponding sample sizes
#' @param rs The sequence of rs that should be tested. r should run up to 2
(higher values are implausible; E.-J. Wagenmakers, personal communication,
Aug 22, 2013)
#' @param labels Names for the studies (displayed in the facet headings)
#' @param dots Values of r's which should be marked with a red dot
#' @param plot If TRUE, a ggplot is returned. If false, a data frame with
the computed Bayes factors is returned
#' @param sides If set to "two" (default), a two-sided Bayes factor is
computed. If set to "one", a one-sided Bayes factor is computed. In this
case, it is assumed that positive t values correspond to results in the
predicted direction and negative t values to results in the unpredicted
direction. For details, see Wagenmakers, E. J., & Morey, R. D. (2013).
Simple relation between one-sided and two-sided Bayesian point-null
hypothesis tests.
#' @param nrow Number of rows of the faceted plot.
#' @param forH1 Defines the direction of the BF. If forH1 is TRUE, BF > 1
speak in favor of H1 (i.e., the quotient is defined as H1/H0). If forH1 is
FALSE, it's the reverse direction.
#'
#' @references
#'
#' Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G.
(2009). Bayesian t-tests for accepting and rejecting the null hypothesis.
Psychonomic Bulletin and Review, 16, 225-237.
#' Wagenmakers, E.-J., & Morey, R. D. (2013). Simple relation between one-
sided and two-sided Bayesian point-null hypothesis tests. Manuscript
submitted for publication
#' Wagenmakers, E.-J., Wetzels, R., Borsboom, D., Kievit, R. & van der
Maas, H. L. J. (2011). Yes, psychologists must change the way they analyze
their data: Clarifications for Bem, Utts, & Johnson (2011)

BFrobustplot <- function(
  ts, ns, rs=seq(0, 2, length.out=200), dots=1, plot=TRUE,
  labels=c(), sides="two", nrow=2, xticks=3, forH1=TRUE)
{
  library(BayesFactor)
```

```
  # compute one-sided p-values from ts and ns
  ps <- pt(ts, df=ns-1, lower.tail = FALSE)   # one-sided test

  # add the dots location to the sequences of r's
  rs <- c(rs, dots)

  res <- data.frame()
  for (r in rs) {

    # first: calculate two-sided BF
    B_e0 <- c()
    for (i in 1:length(ts))
      B_e0 <- c(B_e0, exp(ttest.tstat(t = ts[i], n1 = ns[i],
rscale=r)$bf))

    # second: calculate one-sided BF
    B_r0 <- c()
    for (i in 1:length(ts)) {
      if (ts[i] > 0) {
        # correct direction
        B_r0 <- c(B_r0, (2 - 2*ps[i])*B_e0[i])
      } else {
        # wrong direction
        B_r0 <- c(B_r0, (1 - ps[i])*2*B_e0[i])
      }
    }

    res0 <- data.frame(t=ts, n=ns, BF_two=B_e0, BF_one=B_r0, r=r)
    if (length(labels) > 0) {
      res0$labels <- labels
      res0$heading <- factor(1:length(labels), labels=paste0(labels, "\n(t
= ", ts, ", df = ", ns-1, ")"), ordered=TRUE)
    } else {
      res0$heading <- factor(1:length(ts), labels=paste0("t = ", ts, ", df
= ", ns-1), ordered=TRUE)
    }
    res <- rbind(res, res0)
  }

  # define the measure to be plotted: one- or two-sided?
  res$BF <- res[, paste0("BF_", sides)]


  # Flip BF if requested
  if (forH1 == FALSE) {
    res$BF <- 1/res$BF
  }


  if (plot==TRUE) {
    library(ggplot2)
    p1 <- ggplot(res, aes(x=r, y=log(BF))) + geom_line() +
facet_wrap(~heading, nrow=nrow) + theme_bw() + ylab("log(BF)")
    p1 <- p1 + geom_hline(yintercept=c(c(-log(c(30, 10, 3)), log(c(3, 10,
30)))), linetype="dotted", color="darkgrey")
    p1 <- p1 + geom_hline(yintercept=log(1), linetype="dashed",
color="darkgreen")

    # add the dots
```

```
    p1 <- p1 + geom_point(data=res[res$r %in% dots,], aes(x=r,
y=log(BF)), color="red", size=2)

    # add annotation
    p1 <- p1 + annotate("text", x=max(rs)*1.8, y=-2.85,
label=paste0("Strong~H[", ifelse(forH1==TRUE,0,1), "]"), hjust=1,
vjust=.5, size=3, color="black", parse=TRUE)
    p1 <- p1 + annotate("text", x=max(rs)*1.8, y=-1.7 ,
label=paste0("Moderate~H[", ifelse(forH1==TRUE,0,1), "]"), hjust=1,
vjust=.5, size=3, color="black", parse=TRUE)
    p1 <- p1 + annotate("text", x=max(rs)*1.8, y=-.55 ,
label=paste0("Anectodal~H[", ifelse(forH1==TRUE,0,1), "]"), hjust=1,
vjust=.5, size=3, color="black", parse=TRUE)
    p1 <- p1 + annotate("text", x=max(rs)*1.8, y=2.86 ,
label=paste0("Strong~H[", ifelse(forH1==TRUE,1,0), "]"), hjust=1,
vjust=.5, size=3, color="black", parse=TRUE)
    p1 <- p1 + annotate("text", x=max(rs)*1.8, y=1.7  ,
label=paste0("Moderate~H[", ifelse(forH1==TRUE,1,0), "]"), hjust=1,
vjust=.5, size=3, color="black", parse=TRUE)
    p1 <- p1 + annotate("text", x=max(rs)*1.8, y=.55  ,
label=paste0("Anectodal~H[", ifelse(forH1==TRUE,1,0), "]"), hjust=1,
vjust=.5, vjust=.5, size=3, color="black", parse=TRUE)

    # set scale ticks
    p1 <- p1 + scale_y_continuous(breaks=c(c(-log(c(30, 10, 3)), 0,
log(c(3, 10, 30)))), labels=c("-log(30)", "-log(10)", "-log(3)", "log(1)",
"log(3)", "log(10)", "log(30)"))
    p1 <- p1 + scale_x_continuous(breaks=seq(min(rs), max(rs),
length.out=xticks))

    return(p1)
  } else {
    return(res)
  }
}


# white data two sided
BFrobustplot(
  ts=c(2.18, -2.39, -4.58, 4.78, -1.92, 4.51, -3.44, -6.08),
  ns=c(49, 49, 19, 19, 40, 40, 11, 11),
  dots=1, sides="two", forH1 = FALSE)
```
Code 3. R code associated with the Bayesian reanalysis of the NHST results reported by White et al. (2014).

Appendix B Experiment 1

Appendix B1 Embodied cognition and conceptual metaphor theory: The role of brightness perception in affective and attitudinal judgments

"*The words of language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be "voluntarily" reproduced and combined. […] The above mentioned elements are, in my case, of visual and some of muscular type*"

— Albert Einstein[236]

How do humans think about things they cannot see, hear, touch, smell or taste? The ability to think and communicate about abstract domains such as emotion, morality, or mathematics is presumably uniquely human, and one of the hallmarks of human sophistication. Up to date the question how people represent these abstract domains mentally has not been answered definitely. Earlier classical cognitive models act on the Cartesian assumption of the disembodiment of mind (or soul, in Descartes terms). These models assume that neurological events can explain thought and related notions to the full extend. This view conforms to the computer metaphor of the mind in which thinking is solely based on brain activity or, in computer terminology, based on the central processing unit, also more commonly known as CPU (Seitz, 2000).

[236] As quoted in Hadamard, 1996, The mathematician's mind: The psychology of invention in the mathematical field. Princeton, NJ: Princeton University Press (original work published 1945), as cited in Diezmann, C. M., & Watters, J. J. (2000). Identifying and supporting spatial intelligence in young children. Contemporary Issues in Early Childhood. 1(3), 299-313).

When the body is put back into thought (embodied cognition) a very different perspective on human thinking emerges, namely, that we are not simply inhabitants of our body; we literally use it to think. Perhaps sensory and motor representations that develop from physical interactions with the external world (i.c., vertical dimensions) are recycled to assist our thinking about abstract phenomena. This hypothesis evolved, in part, by patterns observed in language. In order to communicate about abstract things, people often utilize metaphors from more concrete perceptual domains. For example, people experiencing positive affect are said to be feeling “up” whereas people experiencing negative affect are said to be feeling “down”. Cognitive linguists studying cognitive semantics (e.g., Gibbs, 1992; Glucksberg, 2001) have argued such articulations reveal that people conceptualize abstract concepts like affect metaphorically, in terms of physical reality (i.c., verticality). It has been argued that without such links, abstract concepts would lack common ground and would be difficult to convey to other people (Meier & Robinson, 2004). This approach helped scholars to draw significant links between embodied experience, abstract concepts, and conceptual metaphors.

Conceptual Metaphor Theory

The Conceptual Metaphor Theory (Lakoff & Johnson, 1980) defines two basic roles for conceptual domains posited in conceptual metaphors: the source domain (the conceptual domain from which metaphorical expressions are drawn) and the target domain (the conceptual domain to be understood). Conceptual metaphors usually refer to an abstract concept as target and make use of concrete physical entities as their source. For example, morality is an abstract concept and when people discuss morality they recruit metaphors that tap vertical space (a concrete physical concept). In colloquial language a person who is moral is described as ‘‘high minded’’, whereas an immoral person might be denominated as ‘‘down and dirty’’ (Lakoff & Johnson, 1999). Following theory the human tendency for categorization is structured by imagistic, metaphoric, and schematizing abilities that are themselves embedded in the biological motor and perceptual infrastructure (Jackson, 1983). Supporters of this view suggest that cognition, rather than being amodal, is by nature linked to sensation and perception and consequently inherently cross-modal (e.g., Niedenthal, Barsalou, Winkielman & Krauth-Gruber, 2005). Furthermore, those researchers argue for the bodily basis of thought and its continuity beyond the infantile sensorimotor stage (e.g., Seitz, 2000). Indeed, some researchers suggest that the neurological processes that make abstract thought possible are intimately connected with the neurological processes that are responsible for representing perceptual experiences. Specifically, they argue that conceptual thought is based on sensory experience, but sensory experience is not based on conceptual thought (e.g., love is a rose, but a rose is a rose) (Meier & Robinson, 2005).

Why is an abstract concept like affect so frequently linked to concrete qualities like vertical position? One possible explanation for this perceptual-conceptual connection comes from developmental research. Early theorists of sensorimotor learning and development emphasized the importance of movement in cognitive development (e.g., Piaget, 1952). According to this perspective, human cognition develops through sensorimotor experiences. Young children in the sensorimotor stage (from birth to about age two) think and reason about things that they can see, hear, touch, smell or taste. Motor skills emerge and the infant cultivates the coordination of tactile and visual information. Later researchers postulated that thinking is an extended form of those skilled behaviours and that it is based on these earlier modes of adaptation to the physical environment (Bartlett, 1958). For example, it has been suggested that gesture and speech form parallel systems (McNeill, 1992) and that the body is central to mathematical comprehension (Lakoff & Nunez, 1997).

When children get older they develop the skills to think in abstract terms. These skills maybe built upon earlier sensorimotor representations. For example, a warm bath leads to a pleasant sensory experience and positive affect. In adulthood, this pairing of sensory and abstract representations may give rise to a physical metaphor (e.g., a warm person is a pleasant person) that continues to exert effects on representation and evaluation (Meier & Robinson, 2004). Transferred to the vertical representation of affect one can only speculate. Tolaas (1991) proposes that infants spend much of their time lying on their back. Rewarding stimuli like food and affection arrive from a high vertical position. The caregiver frequently appears in the infant's upper visual-spatial environment (Meier, Sellbom & Wygant, 2007). As children age, they use this sensorimotor foundation to develop abstract thought, as recognized by developmental psychologists (e.g., Piaget & Inhelder, 1969). This early conditioning leads adults to use the vertical dimension when expressing and representing affect. These considerations suggest that the link between affect and vertical position may develop early in the sensorimotor stage (see Gibbs, 2006; for sophisticated considerations).

From theory to experimental applications

Affective metaphors and related associations apply to a multitude of perceptual dimensions such as, for example, spatial location, brightness and tone pitch. A plethora of studies investigated the link between abstract concepts (i.c., affect) and physical representation (i.c., verticality). For example, in a study by Meier and Robinson (2004) participants had to evaluate positive and negative words either above or below a central cue. Evaluations of negative words were faster when words were in the down rather than the up position, whereas evaluations of positive words were faster when words were in the up rather than the down position. In a second study, using a sequential priming paradigm, they showed that evaluations activate spatial attention. Positive word evaluations reduced reaction times for stimuli presented in higher areas of visual space, whereas negative word evaluations reduced reaction times for stimuli presented in lower areas of visual space. A third study revealed that spatial positions do not activate evaluations (e.g., “down” does not activate ‘‘bad’’). Their studies give credit to the assumption that affect has a physical basis.

Moreover, an often-cited study by Wapner, Werner, and Krus (1957) examined the effects of success and failure on verticality related judgements. They found that positive mood states, compared to negative mood states, were associated with line bisections that were higher within vertical space.

In a recent study Meier, Hauser, Robinson, Friesen and Schjeldahl (2007) reported that people have implicit associations between God-Devil and up-down. Their experiments showed that people encode God-related concepts faster if presented in a high (vs. low) vertical position. Moreover, they found that people estimated strangers as more likely to believe in God when their images appeared in a high versus low vertical position.

Another study by Meier and Robinson (2006) correlated individual differences in emotional experience (neuroticism and depression) with reaction times with regard to high (vs. low) spatial probes. The higher the neuroticism or depression of participants, the faster they responded to lower (in contrast to higher) spatial probes. Their results indicate that negative affect influences covert attention in a direction that favours lower regions of visual space. In second experiment the researchers differentiated between neuroticism and depression. They argued that neuroticism is more trait-like in nature than depression (which is more state-like). The researchers concluded from their analysis that depressive symptoms were a stronger predictor of metaphor consistent vertical selective attention than neuroticism.

Similar results emerged when dominance-submission was assessed as an individual difference variable and a covert spatial attention tasks was used to assess biases in vertical selective attention (Robinson, Zabelina, Ode & Moeller, in press). Linking higher levels of dominance to higher levels of perceptual verticality they found that dominant individuals were faster to respond to higher spatial stimuli, whereas submissive individuals were faster to respond to lower spatial stimuli.

Further support for the Conceptual Metaphor Theory comes from a study investing the extent to which verticality is used when encoding moral concepts (Meier, Sellbom & Wygant, 2007). Using a modified IAT1 the researchers showed that people use vertical dimensions when processing moral-related concepts and that psychopathy moderates this effect.

Inspired by the observation that people often use metaphors that make use of vertical positions when they communicate concepts like control and power (e.g. top manager vs. subordinate), some researchers investigated social structure from a social embodiment perspective. For example, Giessner and Schubert (2007) argued that thinking about power involves mental simulation of vertical location. The researchers reported that the description of a powerful leader led participants to place the picture of the leader in an organization chart significantly higher as compared to the description of a non-powerful leader.

As mentioned above, affective metaphors and related associations apply multitudinous perceptual dimensions. Recent research examined the association between stimulus brightness and affect (Meier, Robinson & Clore, 2004). The investigators hypothecated that people automatically infer that bright things are good, whereas dark things are bad (e.g., light of my life, dark times). The researchers found that categorization was inhibited when there was a mismatch between stimulus brightness (white vs. black font) and word valence (positive vs. negative). Negative words were evaluated faster and more accurately when presented in a black font, whereas positive words were evaluated faster and more accurately when presented in a white font. In addition, their research revealed the obligatory nature of this connection.

Furthermore, a series of studies showed that positive word evaluations biased subsequent tone judgment in the direction of high-pitch tones, whereas participants evaluated the same tone as lower in pitch when they evaluated negative words before (Weger, Meier, Robinson & Inhoff, 2007).

In addition, recent experimental work supports the notion that experiences in a concrete domain influence thought about time (an abstract concept). Researchers assume that, in the English language, two prevailing spatial metaphors are used to sequence events in time (e.g., Lakoff & Johnson, 1980). The first is the ego-moving metaphor, in which the observer progresses along a timeline toward the future. The second is the time-moving metaphor, in which "a time-line is conceived as a river or a conveyor belt on which events are moving from the future to the past" (Boroditsky, 2000, p. 5). In an experimental study by Boroditsky and Ramscar (2002), participants had to answer the plurivalent question: "Next Wednesdays meeting has been moved forward two days. What day is the meeting now that it has been rescheduled?" Before asking this ambiguous question, participants were led to think about themselves or another object moving through space. If participants were led to think about themselves as moving forward (ego-moving perspective), then participants answered more often "Friday". On the other hand, if had thought of an object as moving toward themselves (time-moving perspective), then they more often answered "Monday". The researchers showed that those effects do not depend on linguistic priming, per se. They asked the same ambivalent question to people in airports. People who had just left their plane responded more often with Friday than people who were waiting for someone.

Moreover, cognitive psychologists have shown that people employ association between numbers and space. For example, a by study Dehaene, Dupoux and Mehler (1990) showed that probe numbers smaller than a given reference number were responded to faster with the left hand than with the right hand and vice versa. These results indicated spatial coding of numbers on mental digit line. Dehaene, Bossini and Giraux (1993) termed the mentioned association of numbers with spatial left-right response coordinates the SNARC-effect (Spatial-Numerical Association of Response Codes). Another SNARC-effect related issue is that empirical data indicates that associations between negative numbers with left space exist. For example, in a study by Fischer, Warlop, Hill and Fias (2004) participants had to select the larger number compared to a variable reference number of a pair of numbers ranging from –9 to 9. The results showed that negative numbers were associated with left responses and positive numbers with right responses. The mentioned results support the idea that spatial association give access to the abstract representation of numbers. As mentioned above, master mathematicians like Einstein explicitly accentuate the role of the concrete spatial representation of numbers for the development of their mathematical ideas. Today there are a few savants which can do calculation up to 100 decimal places. They also emphasize visuo-spatial imagery as in the case of Daniel Tammet2 who has an extraordinary form of synaesthesia which enables him to visualize numbers in a landscape and to solve huge calculations in the head. Moreover, about 15% of ordinary adults report some form of visuo-spatial representation of numbers (Seron, Pesenti, Noel, Deloche & Cornet, 1992). This implies that the integration of numbers into visuo-spatial coordinates is not a rare phenomenon.

The mentioned studies provide converging empirical evidence that abstract concepts (e.g., affect, trustworthiness) have an astonishing physical basis (e.g. brightness) and that various dimensions of the physical world enable the cognitive system to represent these abstract domains. Therefore, our experimentation can be interpreted in the light of conceptual metaphor theory within the overarching framework of embodied cognition.

Appendix B2 Custom made HTML/JavaScript/ActionScript multimedia website for participant recruitment

```
<!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
"http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
<html xmlns="http://www.w3.org/1999/xhtml">
<head>
<meta http-equiv="Content-Type" content="text/html; charset=utf-8" />
<title>Quantum Cognition</title>
<script src="Scripts/swfobject_modified.js" type="text/javascript"></script>
<style type="text/css">
<!--
body {
    background-color: #000;
}
.center_flash {
    text-align: center;
}
#center_alternative {
    text-align: center;
}
-->
</style>
</head>

<body class="center_flash">
<object id="qp_flash" classid="clsid:D27CDB6E-AE6D-11cf-96B8-444553540000"
width="1024" height="900">
  <param name="movie" value="cover.swf" />
  <param name="quality" value="high" />
```

```
<param name="wmode" value="opaque" />
  <param name="swfversion" value="8.0.35.0" />
  <param name="expressinstall" value="Scripts/expressInstall.swf" />
  <param name="BGCOLOR" value="#000000" />
  <!--[if !IE]>-->
  <object type="application/x-shockwave-flash" data="cover.swf" width="1024"
height="900">
    <!--<![endif]-->
    <param name="quality" value="high" />
    <param name="wmode" value="opaque" />
    <param name="swfversion" value="8.0.35.0" />
    <param name="expressinstall" value="Scripts/expressInstall.swf" />
    <param name="BGCOLOR" value="#000000" />
    <div>
<img id="center_alternative" src="alternative_content.jpg" width="1024"
height="869" border="0" usemap="#Map" />
<map name="Map" id="Map">
  <area shape="rect" coords="2,3,210,85"
href="http://www.cognovo.eu/people/research-fellows/christopher-germann.php"
target="_blank" alt="CogNovo" />
  <area shape="rect" coords="497,560,653,593" href="http://www.cognovo.eu/"
target="_blank" />
  <area shape="rect" coords="677,563,859,592"
href="https://www.plymouth.ac.uk/staff/christopher-harris" target="_blank"
/>
</map>
    </div>
    <!--[if !IE]>-->
  </object>
  <!--<![endif]-->
</object>
<script type="text/javascript">
<!--
swfobject.registerObject("qp_flash");
```

```
//-->
</script>
</body>
</html>
```

Code 4. HTML code with Shockwave Flash® (ActionScript 2.0) embedded via JavaScript.

The online version is available under the following URL:

http://irrational-decisions.com/sona/qp.html

Students were recruited via a cloud-based participant management software (Sona Experiment Management System, Ltd., Tallinn, Estonia; http://www.sona-systems.com) which is hosted on the universities webserver.

Appendix B3 PsychoPy benchmark report

The University of Nottingham

PsychoPy

Psychology software in Python

© Jonathan Peirce. Free software (GNU GPL3+)

Configuration report

Configuration test	**Version or value**	*Notes*
Benchmark		
benchmark version	0.1	*dots & configuration*
full-screen	True	*visual window for drawing*
dots_circle	1600	
dots_square	3300	
available memory	884M	*physical RAM available for configuration test (of 3.2G total)*

PsychoPy

psychopy	1.81.00	*avoid upgrading during an experiment*
locale	English_United Kingdom.1252	*can be set in Preferences -> App*
python version	2.7.3 (32bit)	
wx	2.8.12.0 (msw-unicode)	
pyglet	1.2alpha1	
rush	True	*for high-priority threads*

Visual

openGL version	3.3.0 - Build 8.15.10.2712	
openGL vendor	Intel	
screen size	1920 x 1080	
have shaders	True	

visual sync (refresh)	16.67 ms/frame	*during the drifting GratingStim*
no dropped frames	0 / 180	*during DotStim with 100 random dots*
pyglet avbin	5	*for movies*
openGL max vertices	1200	
GL_ARB_multitexture	True	
GL_EXT_framebuffer_object	True	
GL_ARB_fragment_program	True	
GL_ARB_shader_objects	True	
GL_ARB_vertex_shader	True	
GL_ARB_texture_non_power_of_two	True	
GL_ARB_texture_float	True	
GL_STEREO	**False**	
Audio		
pyo	0.6.6	

Numeric		
numpy	1.9.0	*vector-based (fast) calculations*
scipy	0.14.0	*scientific / numerical*
matplotlib	1.4.0	*plotting; fast contains(), overlaps()*
System		
platform	windowsversion=sys.getwindowsversion(major=6, minor=1, build=7601, platform=2, service_pack='Service Pack 1')	
internet access	True	*for online help, usage statistics, software updates, and google-speech*
auto proxy	True	*try to auto-detect a proxy if needed; see Preferenc*

		es -> *Connections*
proxy setting	--	*current manual proxy setting from Preferences -> Connections*
background processes	**Explorer ...**	*Warning: Some background processes can adversely affect timing*
CPU speed test	0.008 s	*numpy.std() of 1,000,000 data points*

Python packages

PIL	1.1.7
openpyxl	1.5.8
lxml	import ok
setuptools	0.6c11

pytest	2.2.4	
sphinx	1.1.3	
psignifit	--	*could not import package psignifit*
pyserial	2.6	
pp	1.6.2	
pynetstation	import ok	
ioLabs	3.2	
labjack	import ok	
pywin32	--	*could not import package pywin32*
winioport	--	*could not import package winioport*

Appendix B4 Participant briefing

Briefing

On this sheet you will find all the information necessary for you to be able to give informed consent to take part in this experiment. You can ask the experimenter any questions you may have.

This experiment consists of a simple visual discrimination task in which you have to judge the brightness of different shades of grey.

Please remember that you have the right to stop your participation at any time. Also, your data will be kept confidential and the only connection between the two tasks is a participant code to make sure you remain anonymous. It follows that the data-analysis will also be completely anonymous. You have the right to withdraw your data after the experiment. If you care to do so, it will be removed from the analysis.

If you understand all these of these things and if you agree to them, please read and sign the informed consent form on the back of this page.

Appendix B5 Informed consent form

PLYMOUTH UNIVERSITY

School of Psychology

CONSENT TO PARICIPATE IN RESEARCH PROJECT

Researcher: Christopher Germann

Supervisor: Prof. Chris Harris

Topic: Quantum cognition: Visual decision-making

The aim of this research is to study visual decision-making.

Upon finishing the experiment, you will receive a written debriefing with detailed information about the experiment and contact details for more information. You are also welcome to ask any further questions to the experimenter during and after the experiment.

The objectives of this research have been explained to me.

I understand that I am free to withdraw from the research at any stage, and ask for my data to be destroyed if I wish.

I understand that my anonymity is guaranteed, unless I expressly state otherwise.

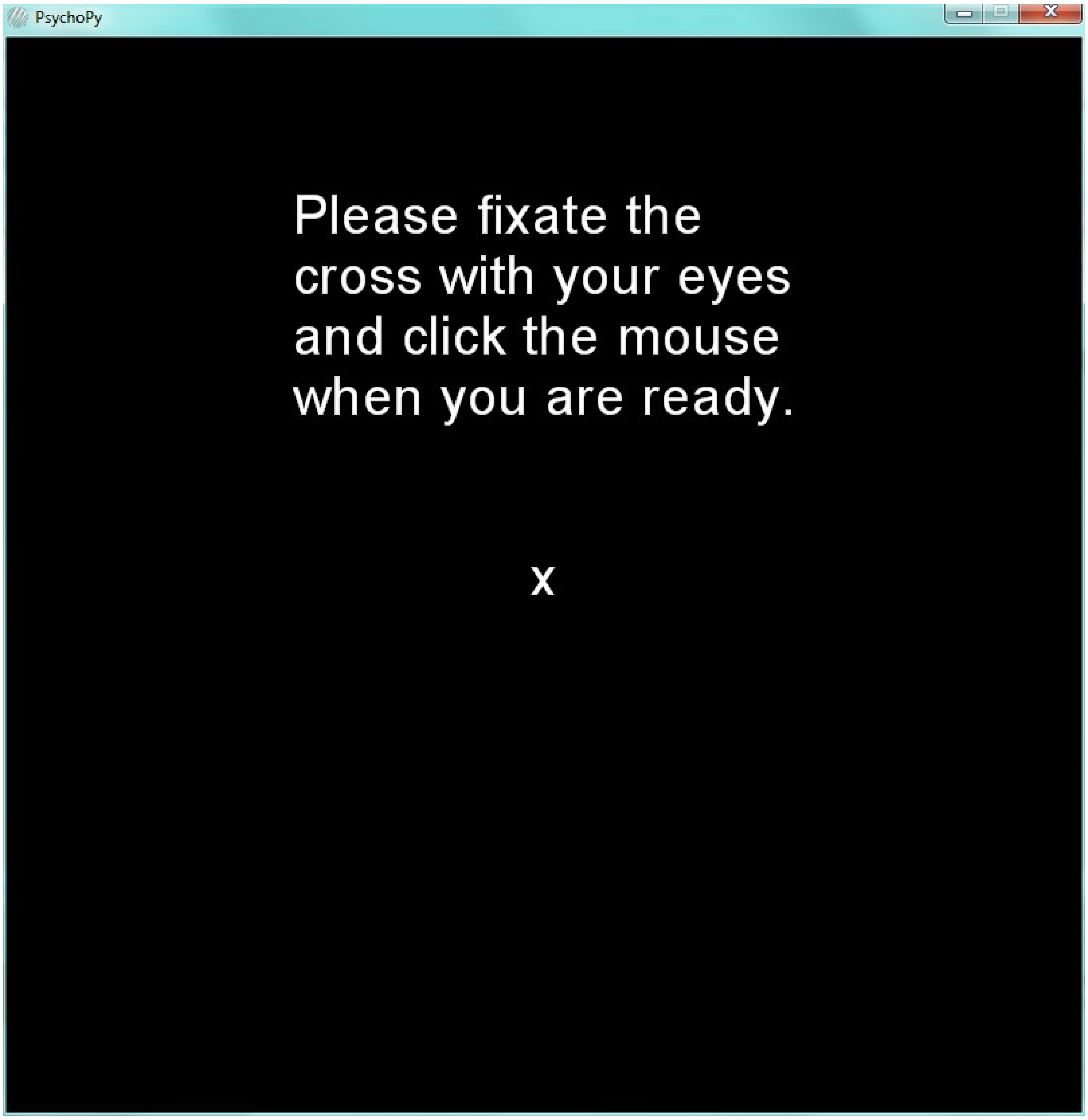
I understand that the Principal Investigator of this work will have attempted, as far as possible, to avoid any risks, and that safety and health risks will have been separately assessed by appropriate authorities (e.g. under COSSH regulations)

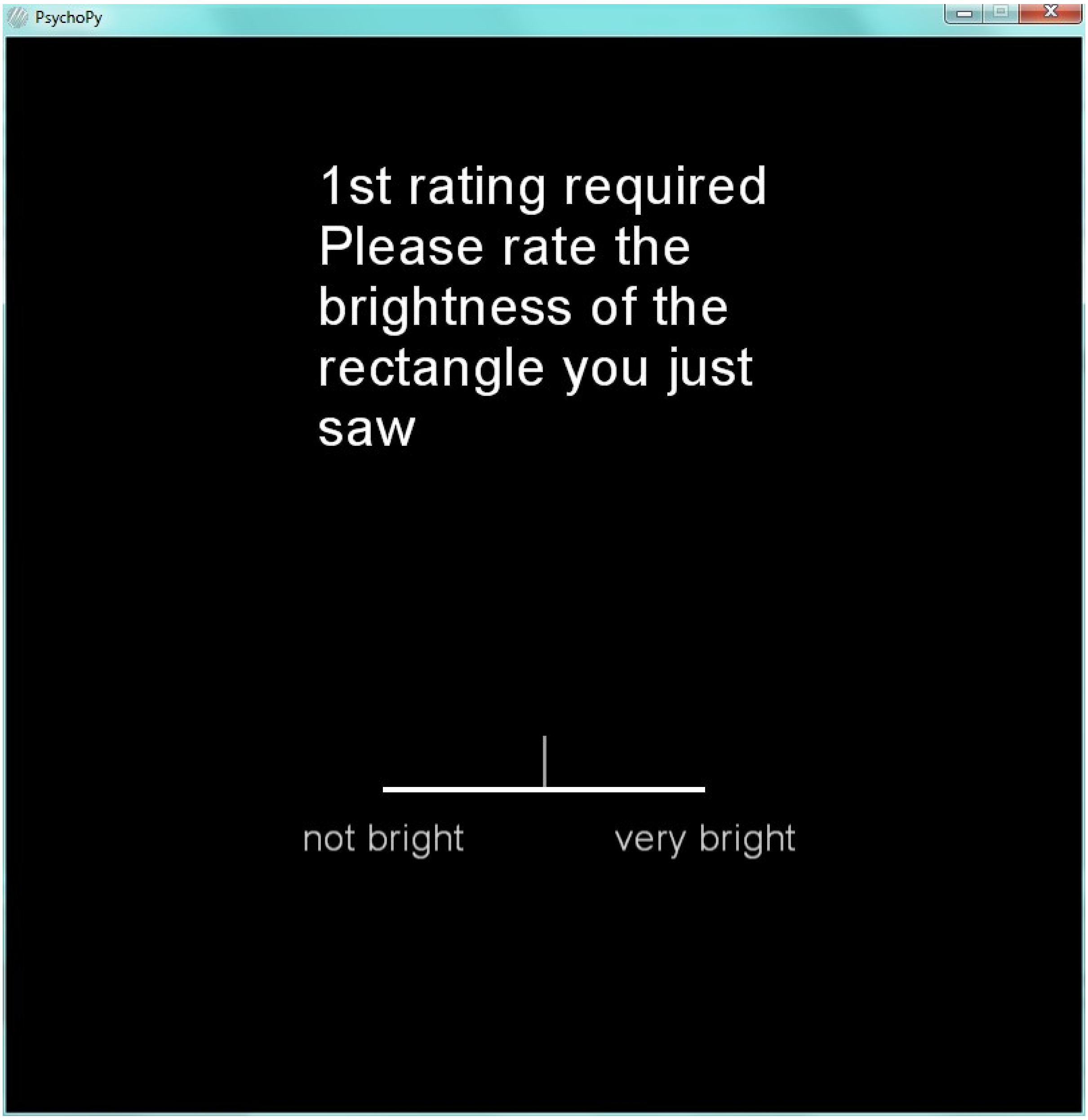
Under these circumstances, I agree to participate in the research.

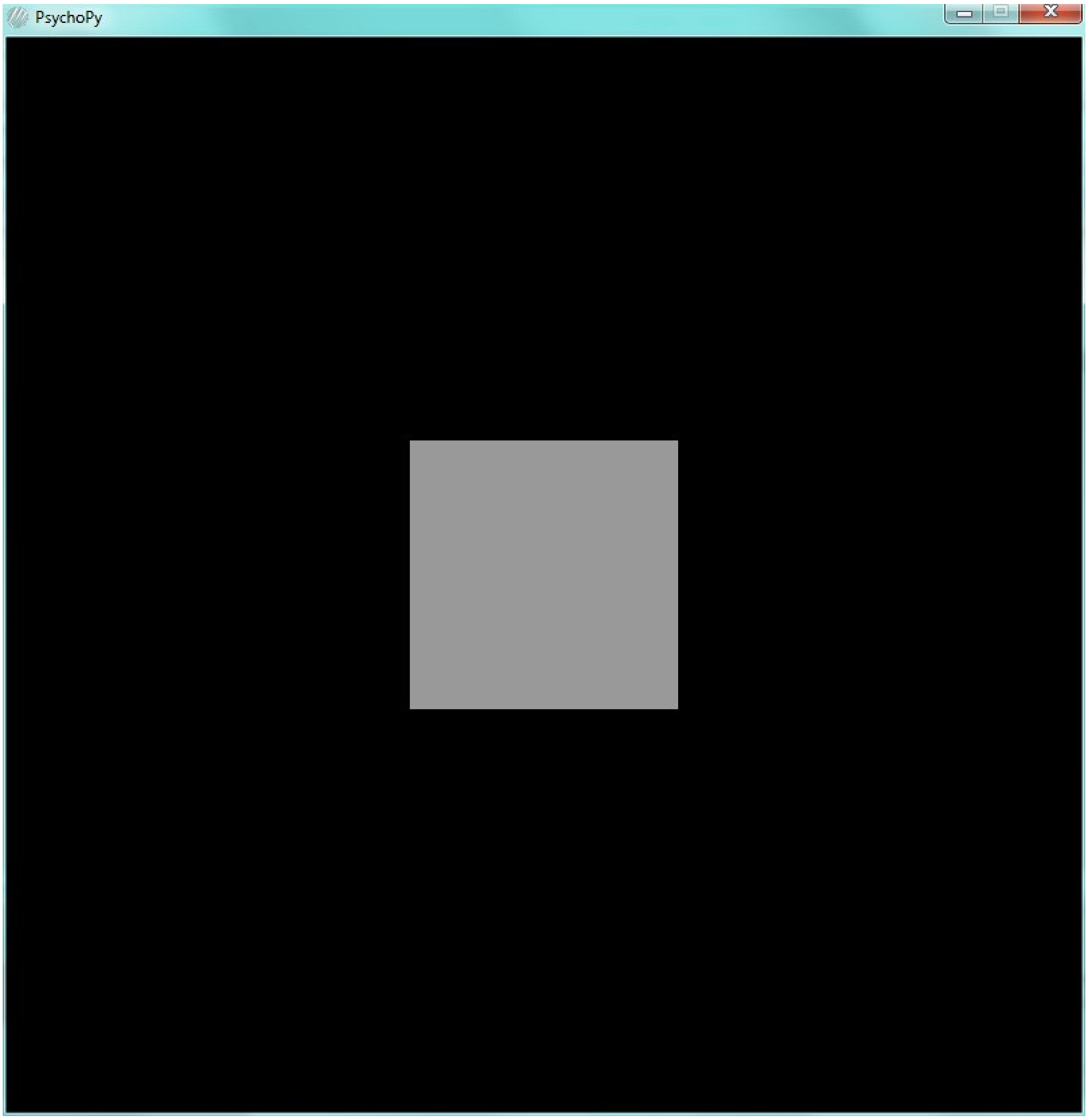
Name: ……………………………………………..…………………………….

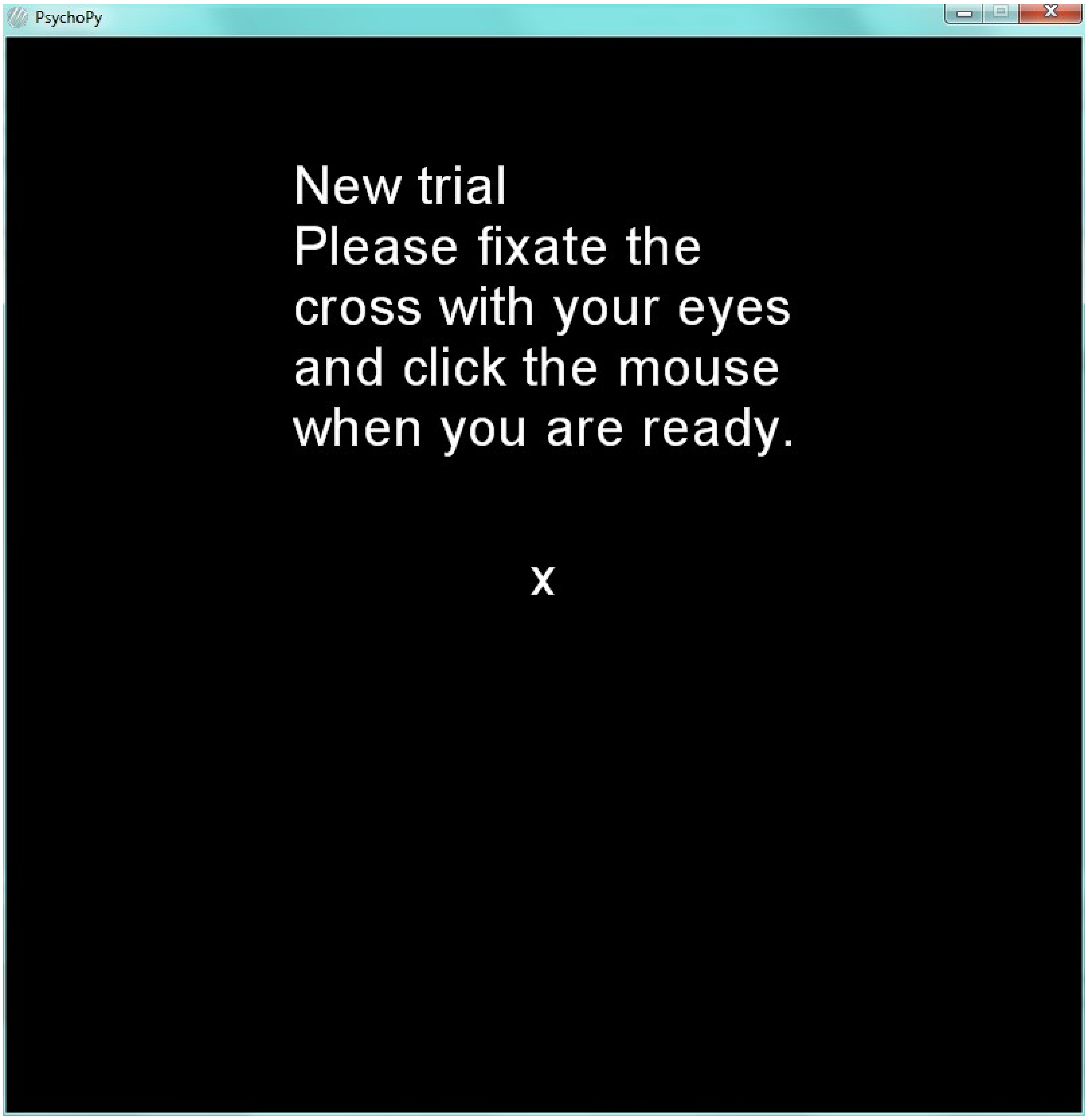
Signature: ....……………….. Date: ....…………..

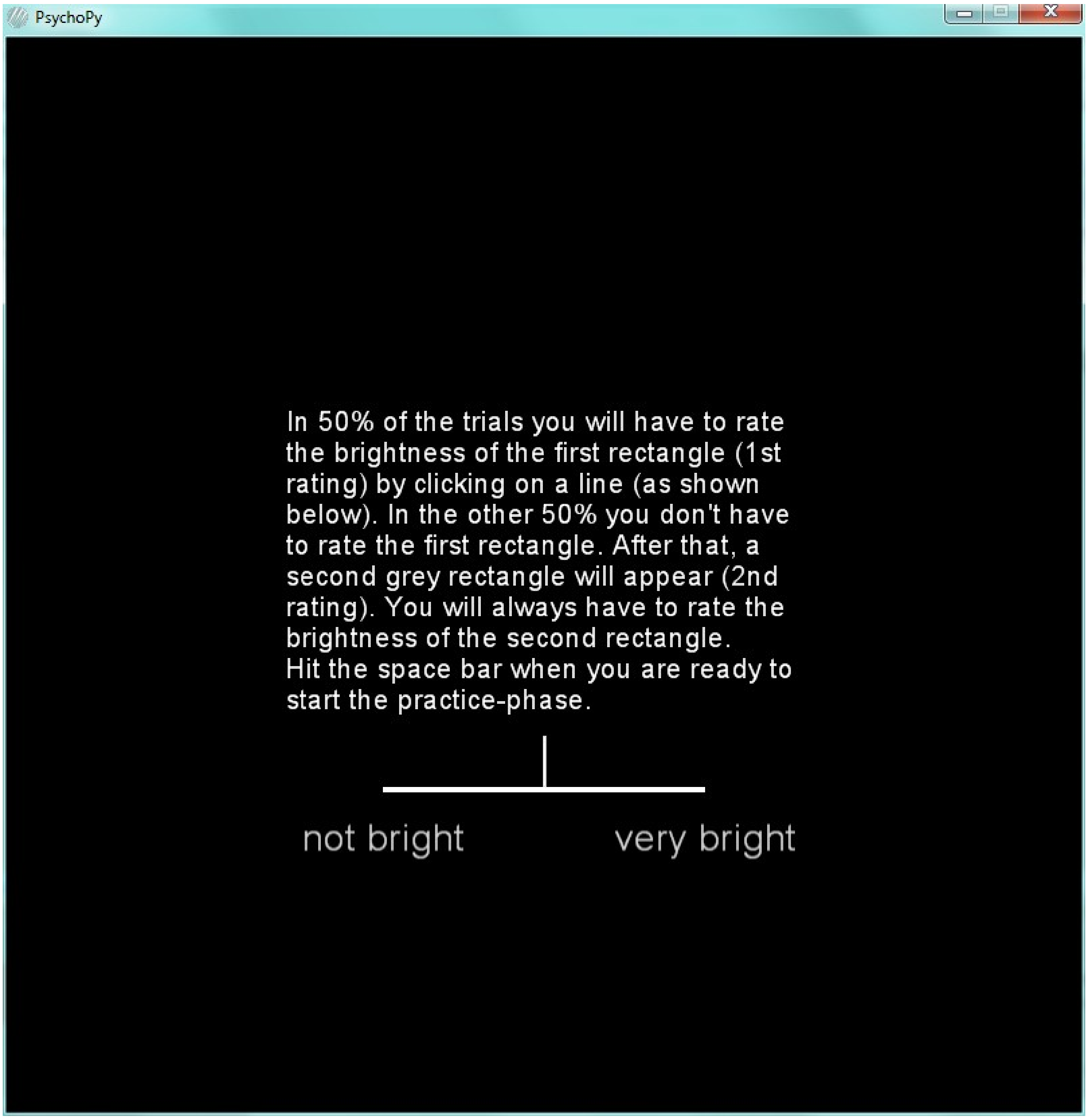
Appendix B6 Verbatim instruction/screenshots

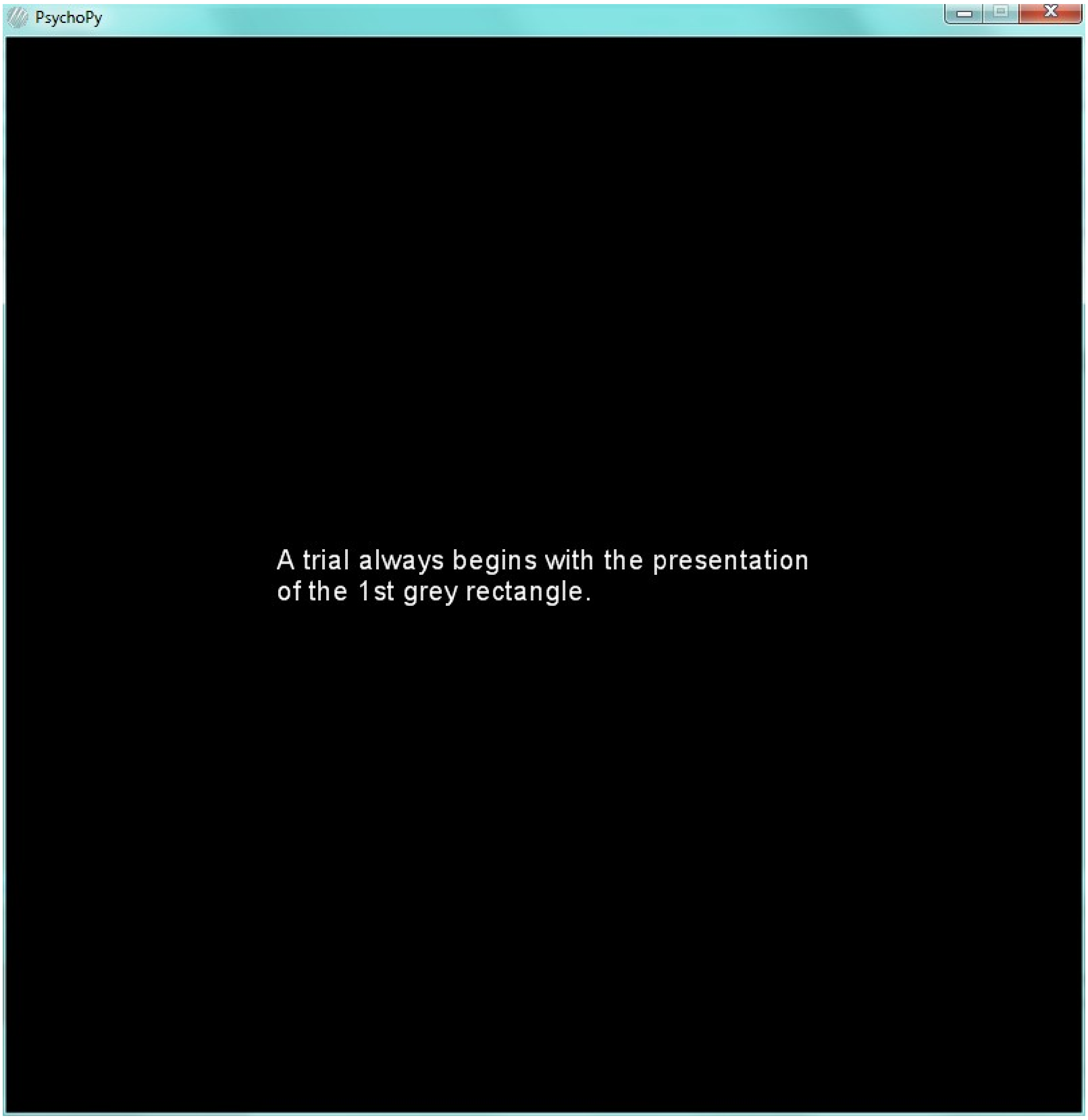


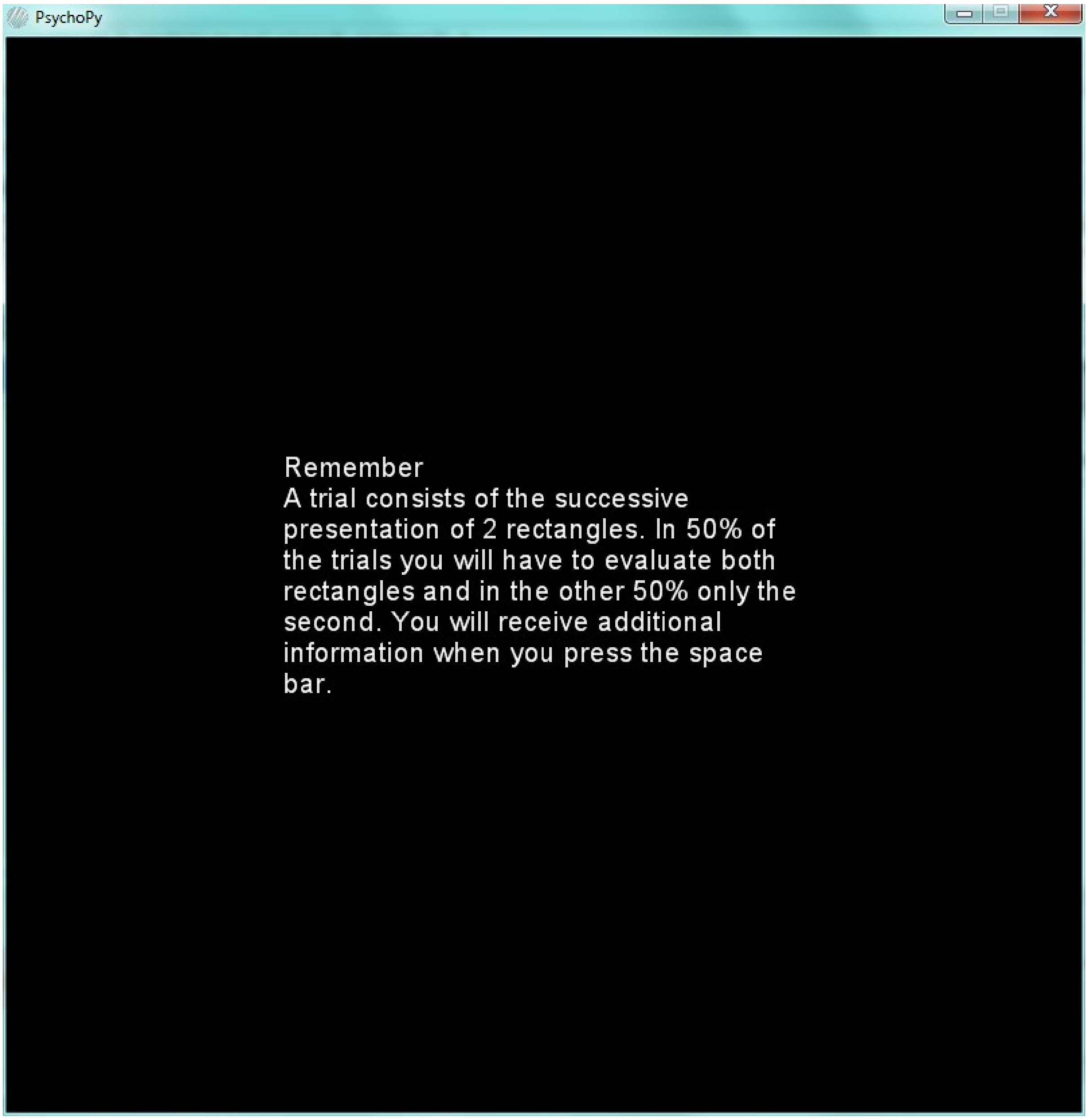

PsychoPy
1st rating required
Please rate the
brightness of the
rectangle you just
saw
not bright
very bright

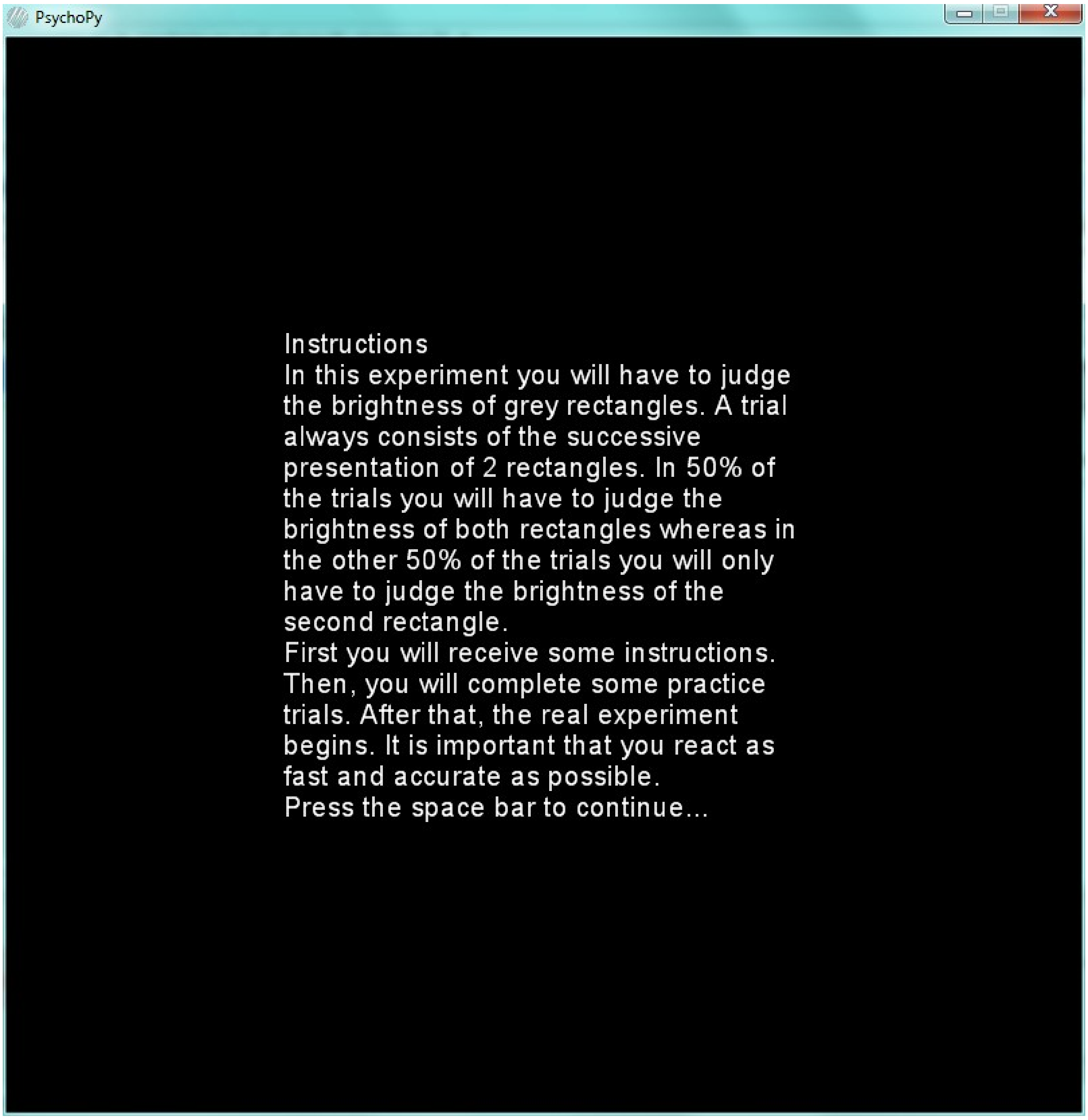

PsychoPy

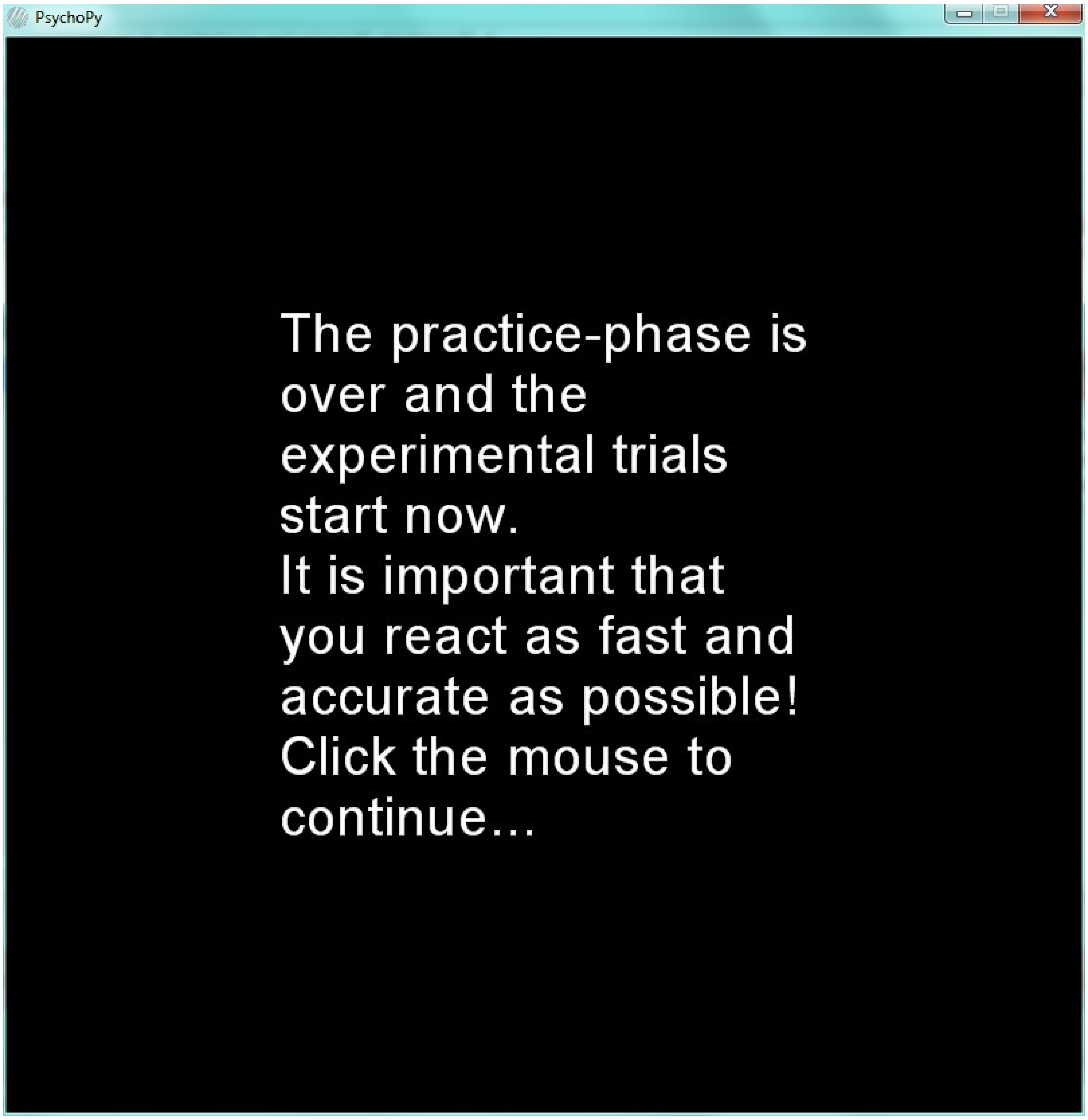

PsychoPy
New trial
Please fixate the
cross with your eyes
and click the mouse
when you are ready.
x

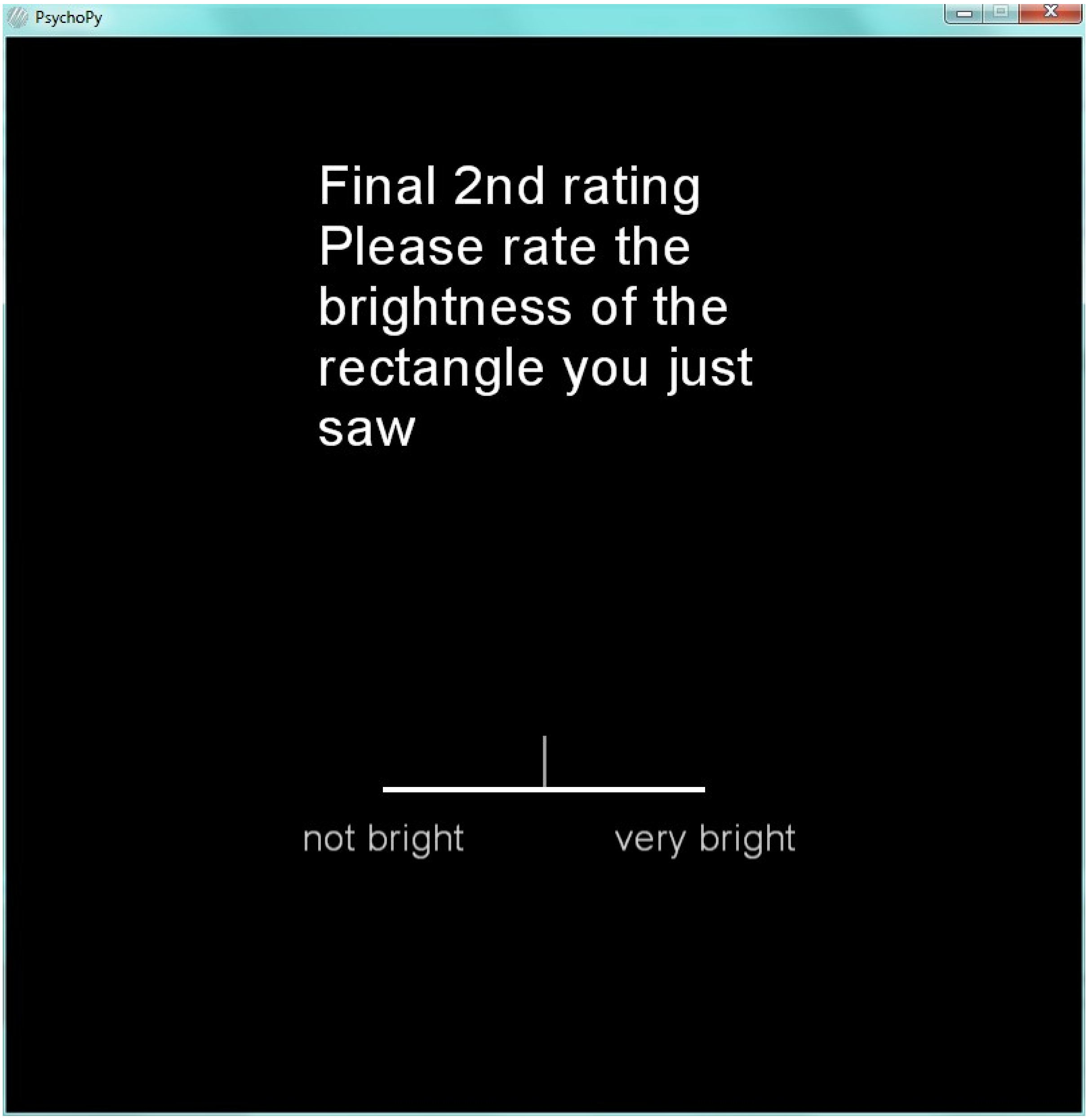

PsychoPy
In 50% of the trials you will have to rate the brightness of the first rectangle (1st rating) by clicking on a line (as shown below). In the other 50% you don't have to rate the first rectangle. After that, a second grey rectangle will appear (2nd rating). You will always have to rate the brightness of the second rectangle.
Hit the space bar when you are ready to start the practice-phase.
not bright
very bright

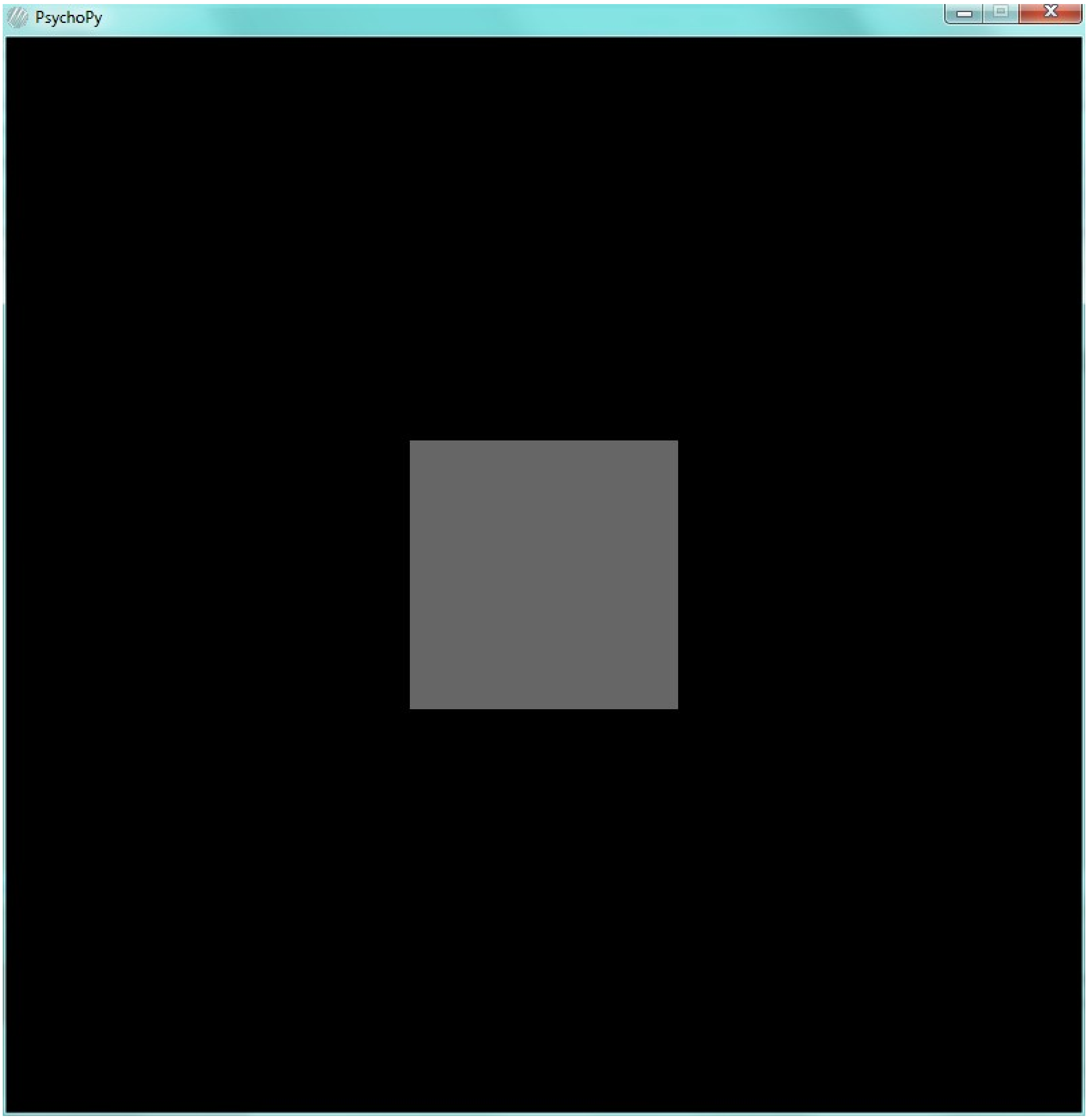

PsychoPy
A trial always begins with the presentation
of the 1st grey rectangle.

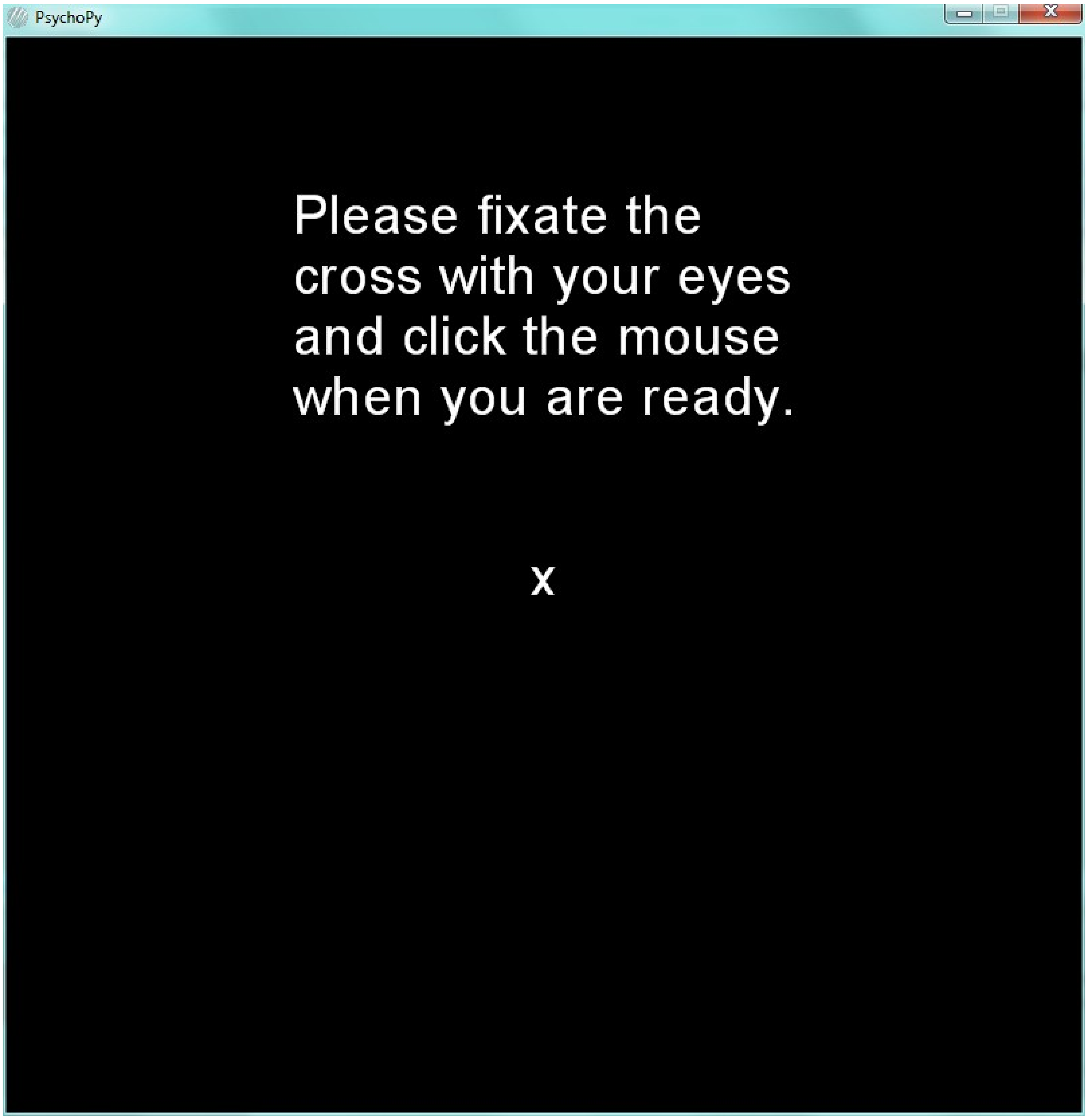

PsychoPy
Remember
A trial consists of the successive presentation of 2 rectangles. In 50% of the trials you will have to evaluate both rectangles and in the other 50% only the second. You will receive additional information when you press the space bar.

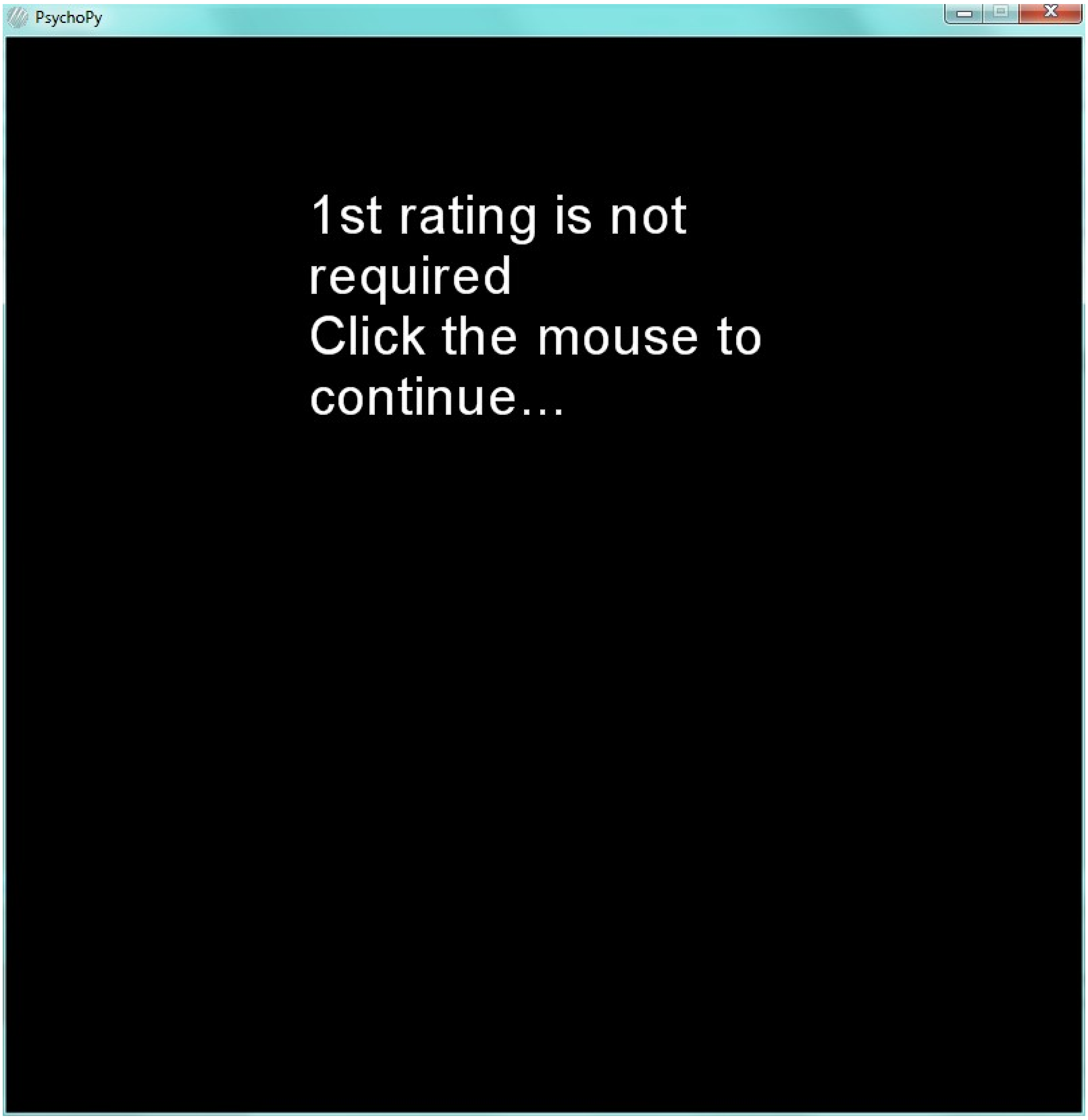

PsychoPy
Instructions
In this experiment you will have to judge the brightness of grey rectangles. A trial always consists of the successive presentation of 2 rectangles. In 50% of the trials you will have to judge the brightness of both rectangles whereas in the other 50% of the trials you will only have to judge the brightness of the second rectangle.
First you will receive some instructions. Then, you will complete some practice trials. After that, the real experiment begins. It is important that you react as fast and accurate as possible.
Press the space bar to continue...

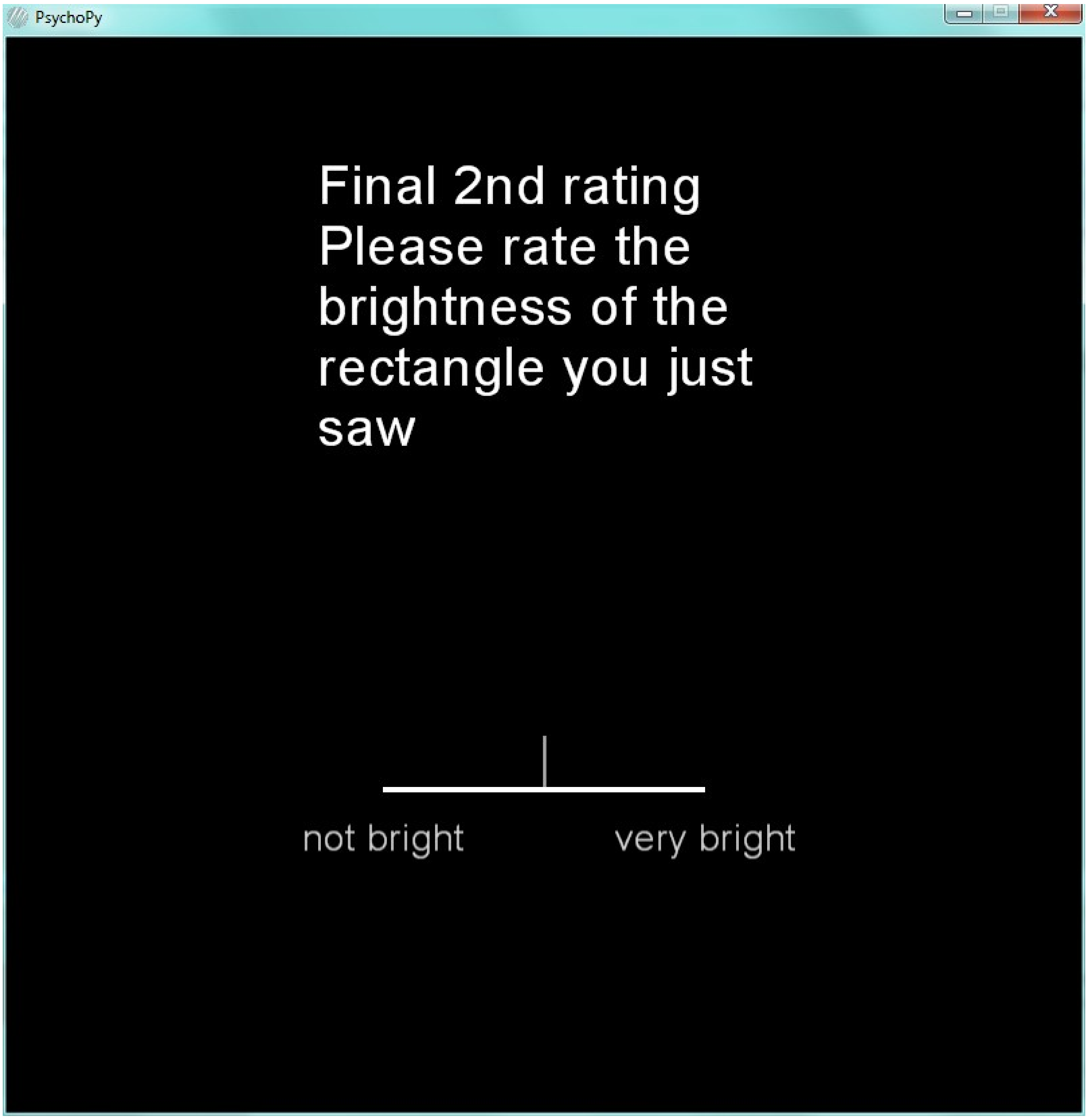

PsychoPy
The practice-phase is over and the experimental trials start now.
It is important that you react as fast and accurate as possible!
Click the mouse to continue...

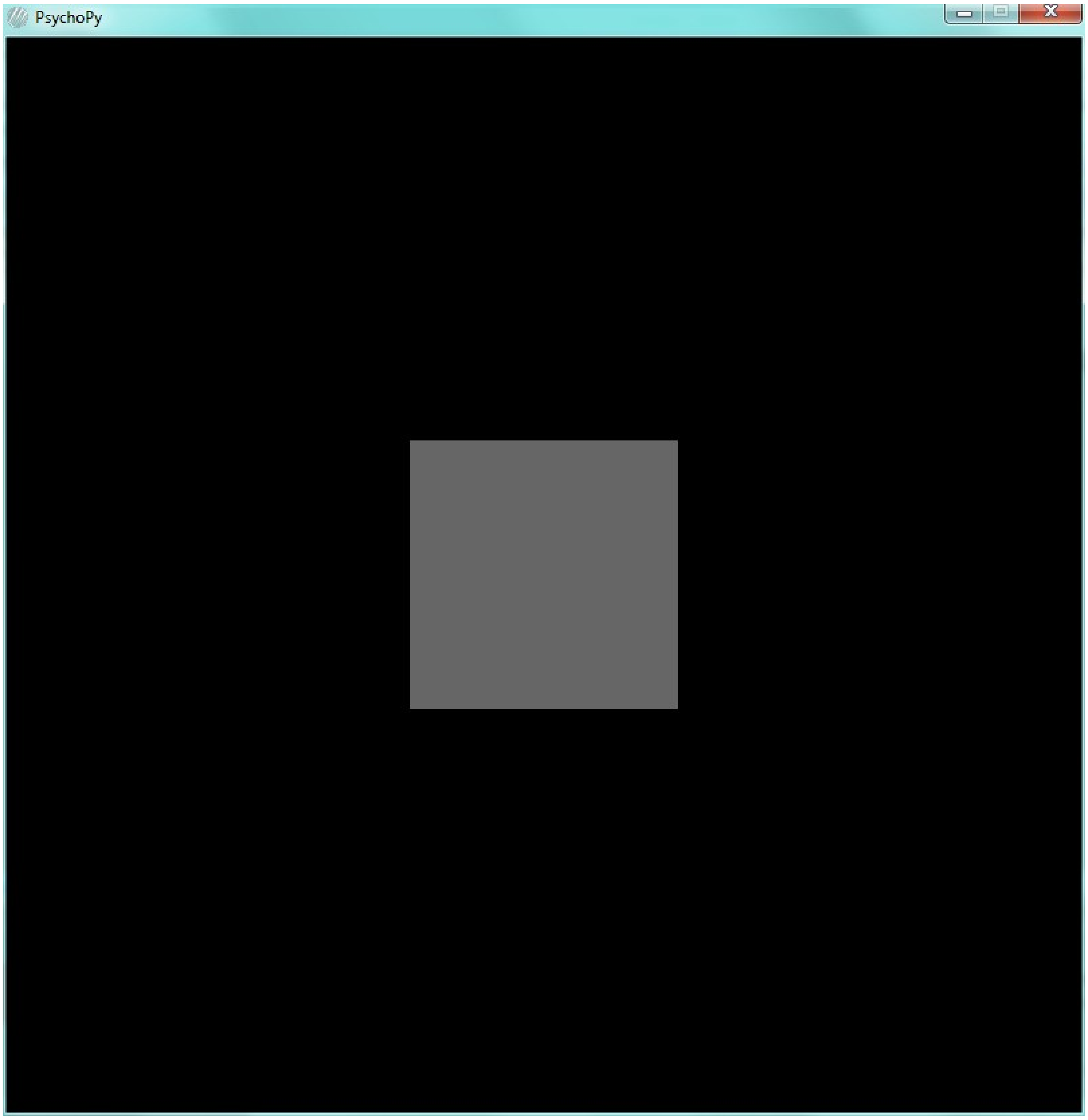

PsychoPy
Final 2nd rating
Please rate the brightness of the rectangle you just saw
not bright
very bright


PsychoPy


PsychoPy
Please fixate the cross with your eyes and click the mouse when you are ready.
X


PsychoPy
1st rating is not required
Click the mouse to continue...


PsychoPy
Final 2nd rating
Please rate the
brightness of the
rectangle you just
saw
not bright
very bright


PsychoPy

Appendix B7 Debriefing

Debrief

Anonymous participant ID: ___________________________

Thank you for participating in this study!

Your participation will help us to investigate order-effects in visual-decision making from a quantum probability perspective.

What is quantum cognition?

Quantum cognition is a newly emerging paradigm within psychology and neuroscience (Pothos & Busemeyer, 2013). It is based on the mathematical framework of quantum theory which provides a general axiomatic theory of probability. This novel approach has the potential to become a viable alternative to classical statistical models.

For general information visit:

http://en.wikipedia.org/wiki/Quantum_cognition

For in depth information we recommend the following paper which is freely available online (see reference below):

http://openaccess.city.ac.uk/2428/

If you have any further questions, or if you want to withdraw you data, please feel free to contact the researcher.

Researcher: Christopher Germann: christopher.germann@plymouth.ac.uk

Supervisor: Prof. Chris Harris: chris.harris@plymouth.ac.uk

References

Pothos, E. M., & Busemeyer, J. R. (2013). Can quantum probability provide a new direction for cognitive modeling. *Behavioral and Brain Sciences*, *36*, 255-274.

Appendix B8 Q-Q plots

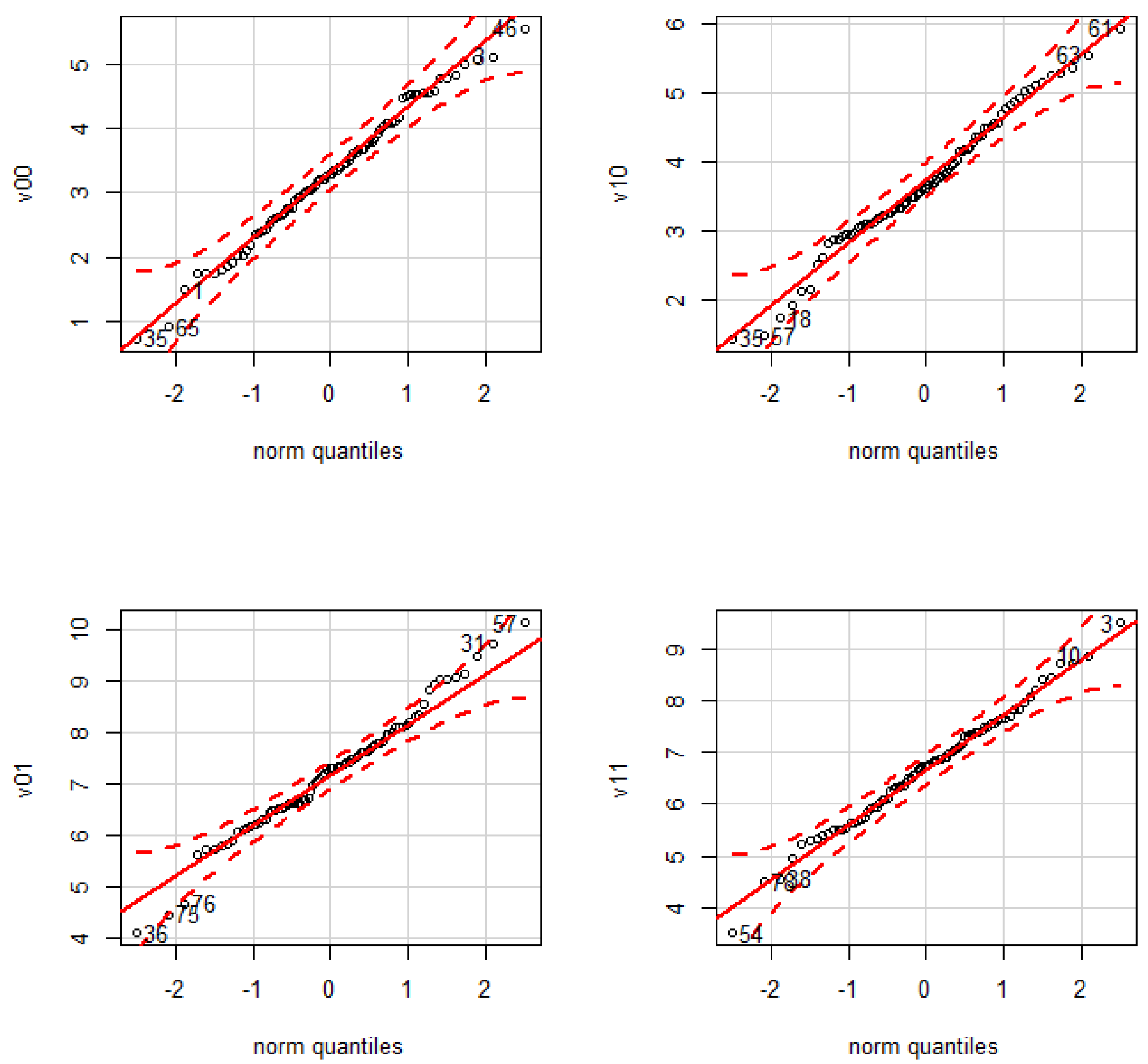


Figure 93. Q-Q plots identifying the 5 most extreme observation per experimental condition (linearity indicates Gaussianity).

Appendix B9 The Cramér-von Mises criterion

Equation 14. The Cramér-von Mises criterion (Cramér, 1936)

$$\omega^2 = \int_{-\infty}^{\infty} [F_n(x) - F^*(x)]^2 \mathrm{d}F^*(x)$$

The criterion can be used to as a goodness-of-index and it's a viable alternative to the more widely used Kolmogorov–Smirnov test. It is eponymously named after Harald Cramér and Richard Edler von Mises who proposed it in 1928–1930.

Appendix B10 Shapiro-Francia test

The Shapiro-Francia test is an analysis of variance test for normality and has good statistical properties (see also the comments by Royston, 1993)

Equation 15. The Shapiro-Francia test (S. S. Shapiro & Francia, 1972)

$$W' = \frac{\mathrm{cov}(x, m)}{\sigma_x \sigma_m} = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(m_i - \overline{m})}{\sqrt{(\sum_{i=1}^{n} (x_i - \overline{x})^2)(\sum_{i=1}^{n} (m_i - \overline{m})^2)}}$$

Appendix B11 Fisher's multivariate skewness and kurtosis

Equation 16. Fisher's multivariate skewness and kurtosis

Skewness = G1
Kurtosis = G2

$$G_1 = \frac{\sqrt{n(n-1)}}{n-2} \cdot \frac{m_3}{m_2^{3/2}},$$

$$G_2 = \frac{n-1}{(n-2)(n-3)} \cdot [(n+1)(\frac{m_4}{m_2^2} - 3) + 6],$$

where

$$m_r = \sum_{i=1}^{n} (x_i - \overline{x})^r / n$$

denotes the r^{th} central moment, $\overline{x}$ the sample mean, and *n* the sample size (Cain et al., 2016).

Appendix B12   Median-based boxplots

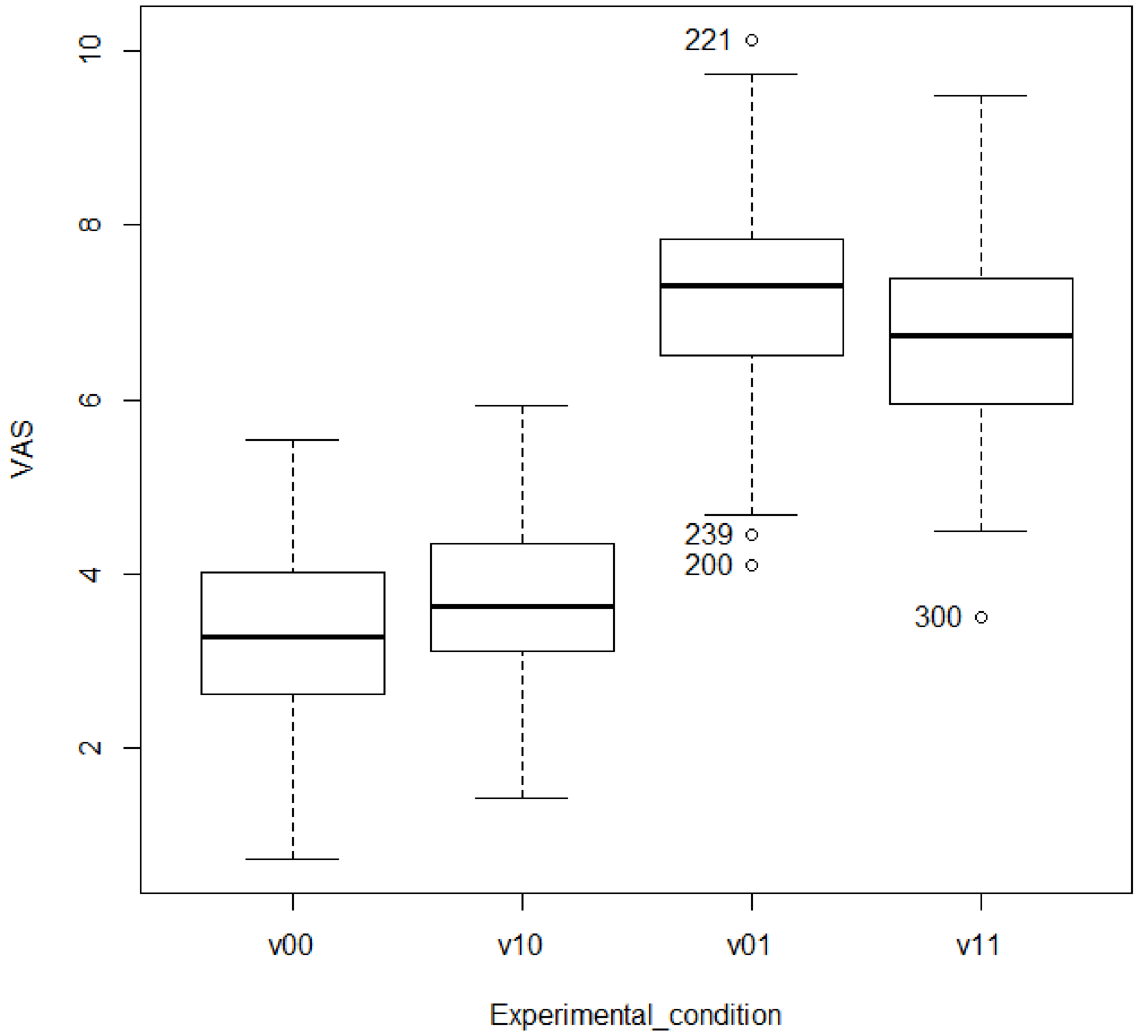


Figure 94. Boxplots visualising differences between experimental conditions (i.e., median, upper and lower quartile).

Note that several potential outliers are identified (i.e., observation “200" "239" "221" "300").

```
#https://cran.r-project.org/web/packages/beanplot/beanplot.pdf
par( mfrow = c( 1, 4 ) )
with(dataexp2, beanplot(v00, ylim = c(0,10), col="lightgray", main =
"v00", kernel = "gaussian", cut = 3, cutmin = -Inf, cutmax = Inf,
overallline = "mean", horizontal = FALSE, side = "no", jitter = NULL,
beanlinewd = 2))
with(dataexp2, beanplot(v01, ylim = c(0,10), col="lightgray", main =
"v01", kernel = "gaussian", cut = 3, cutmin = -Inf, cutmax = Inf,
overallline = "mean", horizontal = FALSE, side = "no", jitter = NULL,
beanlinewd = 2))
with(dataexp2, beanplot(v10, ylim = c(0,10), col="darkgray", main = "v10",
kernel = "gaussian", cut = 3, cutmin = -Inf, cutmax = Inf, overallline =
"mean", horizontal = FALSE, side = "no", jitter = NULL, beanlinewd = 2))
with(dataexp2, beanplot(v11, ylim = c(0,10), col="darkgray", main = "v11",
kernel = "gaussian", cut = 3, cutmin = -Inf, cutmax = Inf, overallline =
"mean", horizontal = FALSE, side = "no", jitter = NULL, beanlinewd = 2))
par( mfrow = c( 1, 2 ) ) ##############################################
with(dataexp2, beanplot(v00, col="darkgray", main = "v00", kernel =
"gaussian", cut = 3, cutmin = -Inf, cutmax = Inf, overallline = "mean",
horizontal = FALSE, side = "no", jitter = NULL, beanlinewd = 2))
with(dataexp2, beanplot(v01, col="darkgray", main = "v01", kernel =
"gaussian", cut = 3, cutmin = -Inf, cutmax = Inf, overallline = "mean",
horizontal = FALSE, side = "no", jitter = NULL, beanlinewd = 2))
par( mfrow = c( 1, 2 ) )
with(dataexp2, beanplot(v10, col="darkgray", main = "v10", kernel =
"gaussian", cut = 3, cutmin = -Inf, cutmax = Inf, overallline = "mean",
horizontal = FALSE, side = "no", jitter = NULL, beanlinewd = 2))
```

```
with(dataexp2, beanplot(v11, col="darkgray", main = "v11", kernel =
"gaussian", cut = 3, cutmin = -Inf, cutmax = Inf, overallline = "mean",
horizontal = FALSE, side = "no", jitter = NULL, beanlinewd = 2))
```

Code 5. R code for symmetric and asymmetric "`beanplots`".

Appendix B13 Tolerance intervals based on the Howe method

The subsequent tolerance intervals (Krishnamoorthy & Mathew, 2008) are based on the Howe method (Howe, 1969) and were computed using the "`tolerance`" R package (Young, 2010). The tolerance interval defines and upper and lower bound between which a given proportion β of the population lies with a prespecified confidence level (1-α). Tolerance intervals circumvent the "robust misinterpretation of confidence intervals", that is, it has been empirically demonstrated that the majority of academics misinterpret conventional confidence intervals (Hoekstra et al., 2014) which can lead to wrong conclusions which can cause serious detrimental real-world consequences.

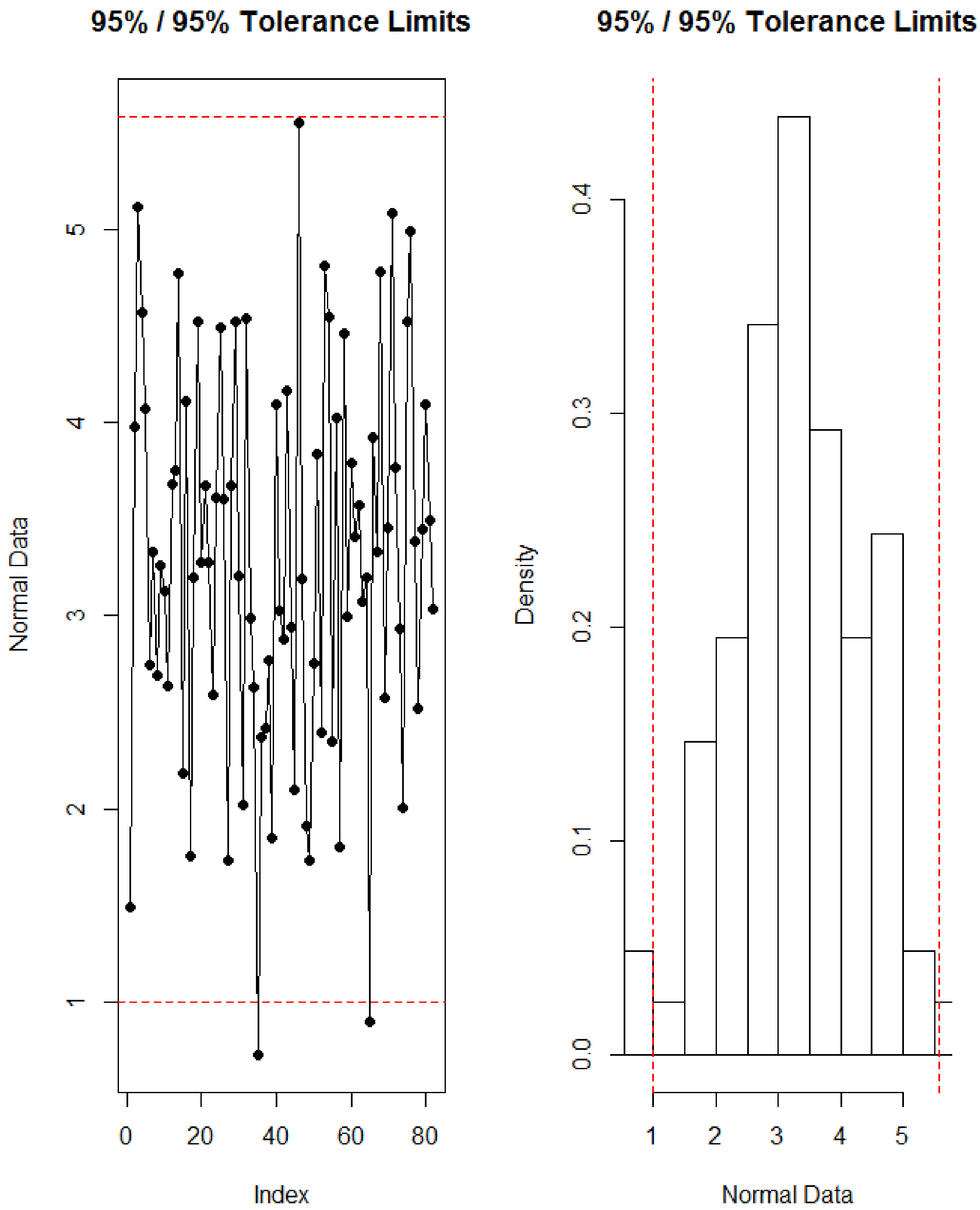


Figure 95. Tolerance interval based on Howe method for experimental condition V_{00}.

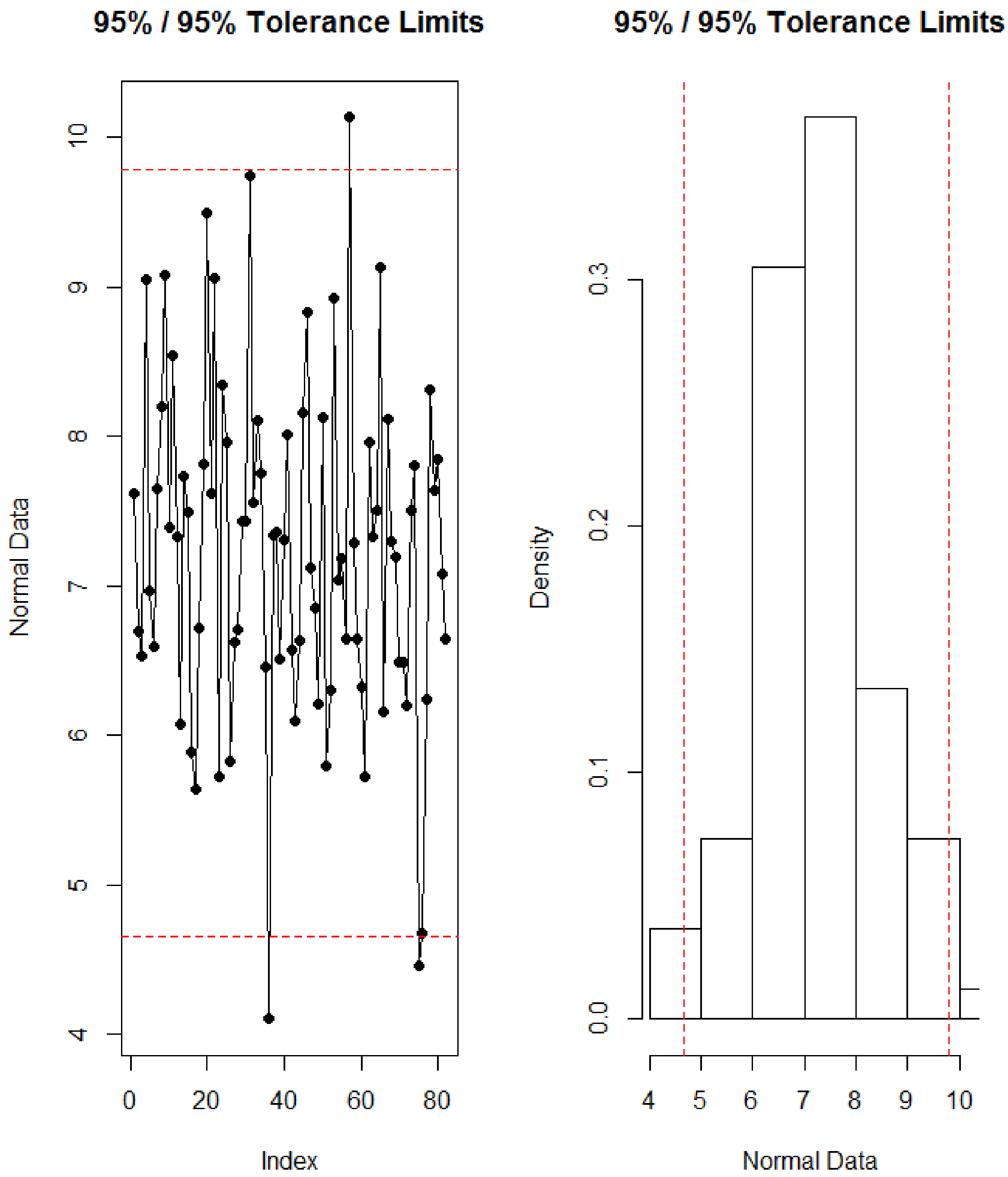


Figure 96. Tolerance interval based on Howe method for experimental condition V_{01}.

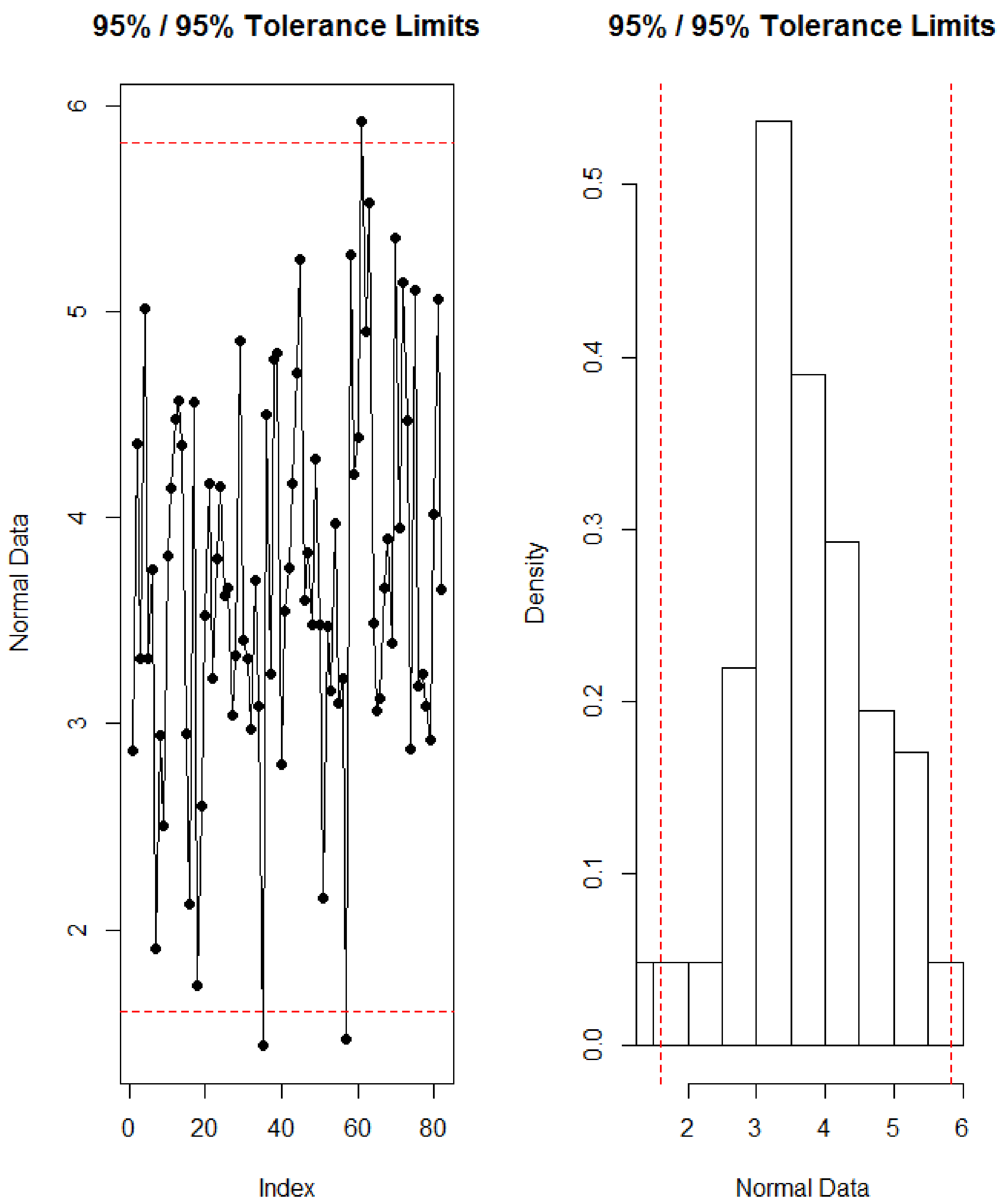


Figure 97. Tolerance interval based on Howe method for experimental condition V_{10}.

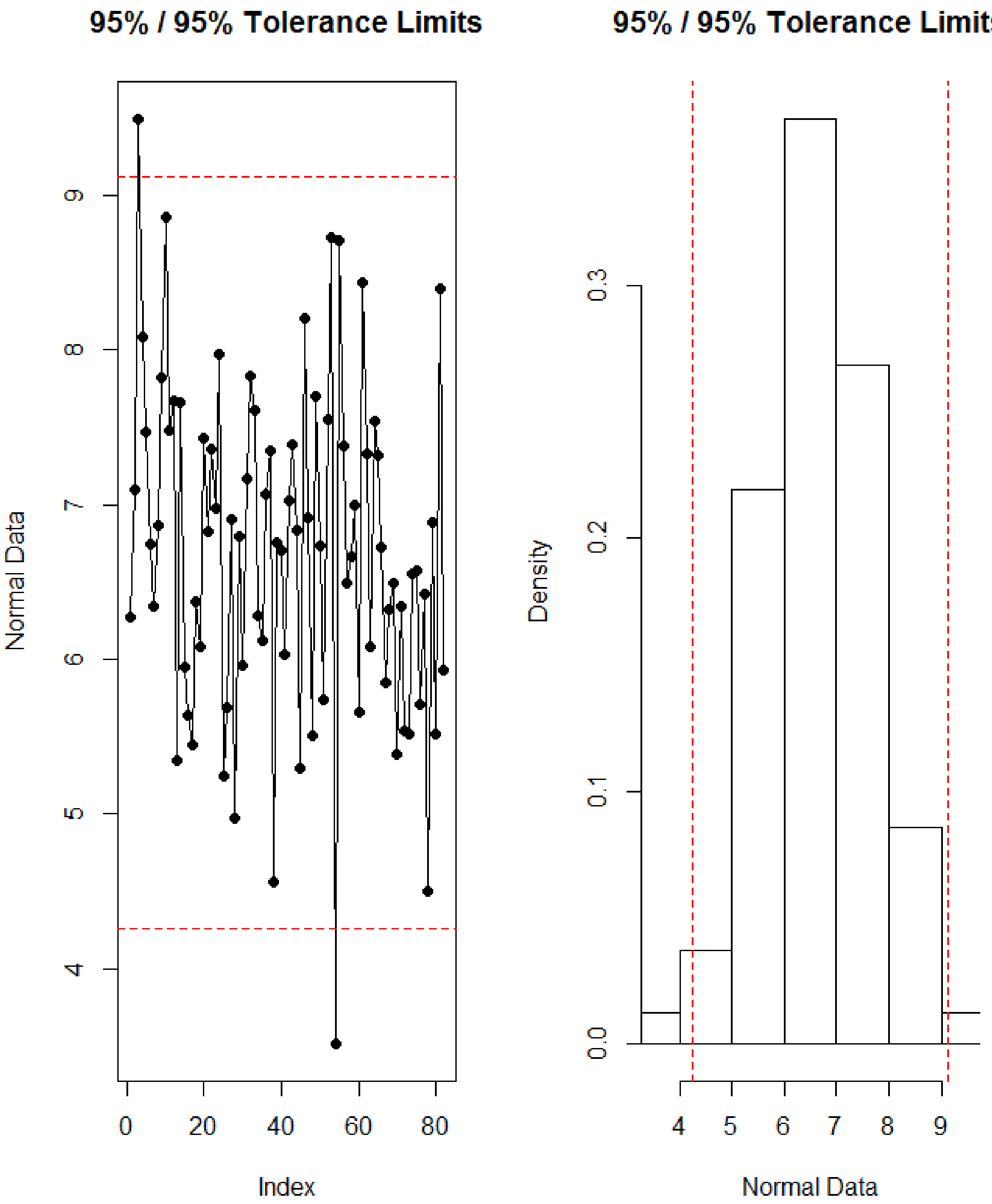


Figure 98. Tolerance interval based on Howe method for experimental condition V_{11}.

Appendix B14 Alternative effect-size indices

It has been noted that “reporting of effect size in the psychological literature is patchy” (Baguley, 2009a, p. 603) even though it is regarded as “best practice” in quantitative research. The decision which effect size metric to report require careful consideration. This can be an issue, given that effortful decision deplete cognitive resources (Baumeister, Vohs, & Tice, 2007).

Even though heuristic “rules of thumb” have been suggested some statistically well versed researchers argue that "canned effect sizes” (Baguley, 2009a, p. 613). This especially true for psychophysical research where differences are often minute but still meaningful. We argue, that effect sizes should be evaluated in context. There are no mechanistic decision-procedures for the classification of effect sizes. These values are always situated and statistical reflection (i.e., cognitive effort) is indispensable. Heuristics vs. analytics: dual system approach (Kahneman, 2003).
Based on Monte Carlo simulations, it has been argued that in order to estimate δ from empirical data, Hedges’s g is regarded as superior to the more widely reported Cohen’s d (Kelley, 2005). The formulaic descriptions of several effect-size metrics are given below.

Equation 17: Cohen's *d* (Cohen, 1988)

$$d = \frac{\overline{x}_1 - \overline{x}_2}{s} = \frac{\mu_1 - \mu_2}{s}.$$

$$s = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

$$s_1^2 = \frac{1}{n_1 - 1} \sum_{i=1}^{n_1} \quad (x_{1,i} - \overline{x}_1)^2,$$

Equation 18: Glass' Δ (Glass, 1976)

$$\Delta = \frac{\overline{x}_1 - \overline{x}_2}{s_2}$$

Equation 19: Hedges' *g* (Hedges, 1981)

$$g = \frac{\overline{x}_1 - \overline{x}_2}{s^*}$$

$$s^* = \sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2-2}}.$$

s^* signifies the pooled and weighted standard deviation. Hence, the defining difference between Hedge’s g and Cohen’s d is that the former integrates pooled weighted standard deviations, whereas the later uses the pooled standard deviations). Whenever standard deviations differ “substantially” between conditions, Glass's Δ should be reported

Appendix B15 Nonparametric bootstrapping

We used nonparametric bootstrapping techniques in order to check the robustness and stability of our results and to maximise statistical inferential power. We performed a bootstrap using the "`boot`" package (Canty & Ripley, 2012) in R for the *t*-tests and the "`BootES`" package (Kirby & Gerlanc, 2013) for the effect sizes and their associated confidence intervals. We obtained bootstrapped confidence intervals for all parameters of interest. Bootstrapping simulations (i.e. resampling with replacement) is a powerful method which facilitates more accurate statistical inferences compared to conventional NHST methods (e.g., bootstrapping is asymptotically more accurate relative to standard CIs based on the Gaussianity assumption and using sample variance). Bootstrap methods do not rely on any assumption regarding the parent distribution from which the bootstrap samples are drawn. As such, bootstrapping "can be remarkably more accurate than classical inferences based on Normal or t distributions" (Hesterberg, 2011, p. 497). The growing popularity of this powerful statistical methodology is linked to recent advances in computational capacities because bootstrapping can be computationally demanding.[237] We choose rather large numbers of bootstrap samples for our analysis (i.e., 100000 replicates per simulation) in order to achieve a high degree of precision.

[237] We utilised an Intel® Core™ i7-2600 processor @ 3.40GHz with 16GB RAM for the reported bootstrap simulations.

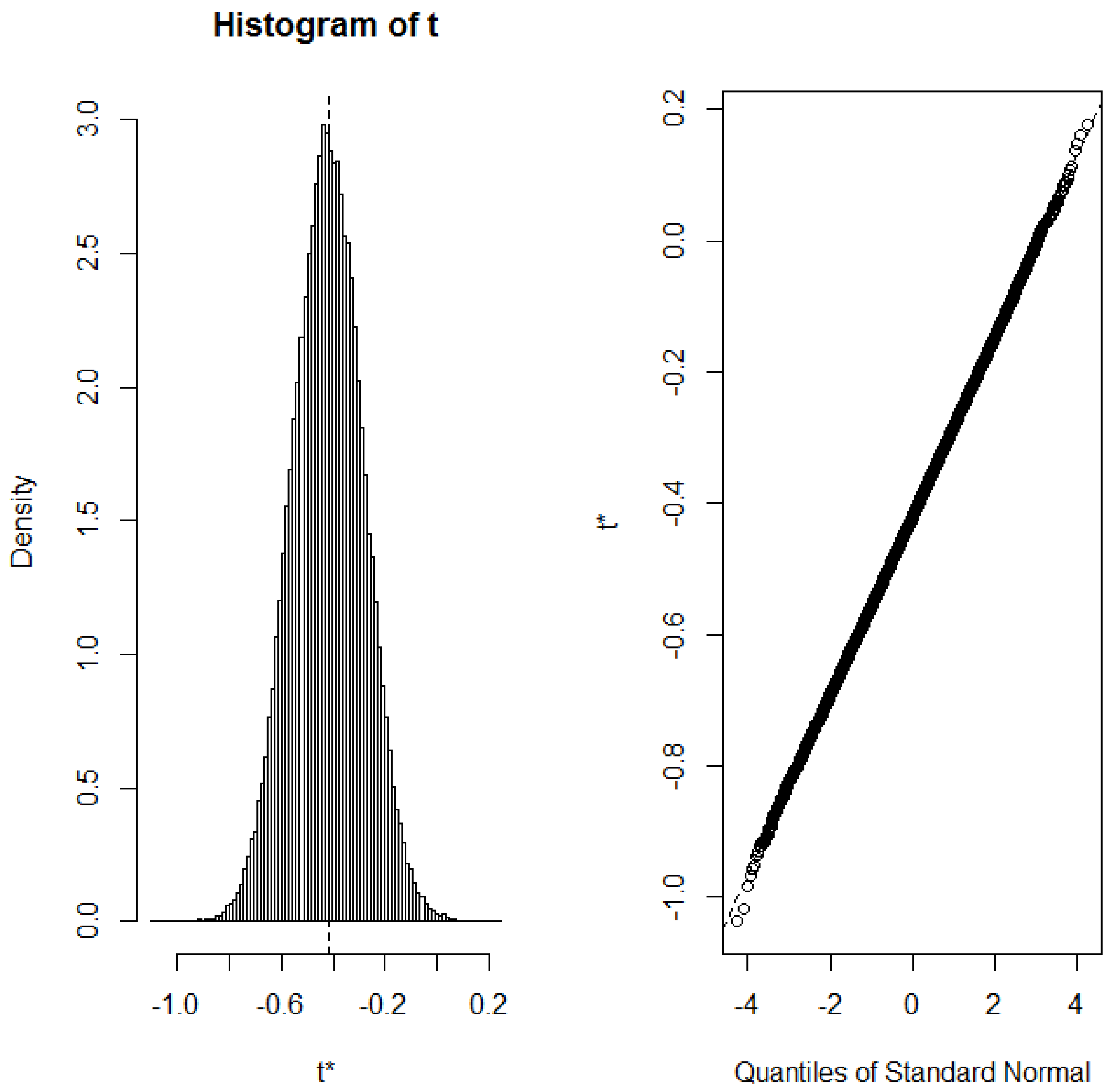


Figure 99. Bootstrapped mean difference for experimental conditions V_{00} vs. V_{10} based on 100000 replicas.

The QQ-plot indicates that the Gaussian distribution has been achieved (due to the central limit theorem), i.e., the number of bootstrap resamples *R* is large enough to obtain parameter estimates with high accuracy.

Table 42

Results of Bca bootstrap analysis (experimental condition V_{00} vs. V_{10}).

```
RESULTS OF BCa BOOTSTRAP FOR DIFF.MEAN

   SUMMARY        Pop.1        Pop.2  n Statistic   Observed
STATISTICS dataexp1$v00 dataexp1$v10 82 diff.mean -0.4200024

BOOTSTRAP Replications       Mean         SE     Bias Percent.bias
  SUMMARY         9999 -0.4194459 0.1350477 0.000557        0.133

CONFIDENCE Level      Type Confidence.interval
  INTERVAL   95% two-sided   (-0.688, -0.1552)
```

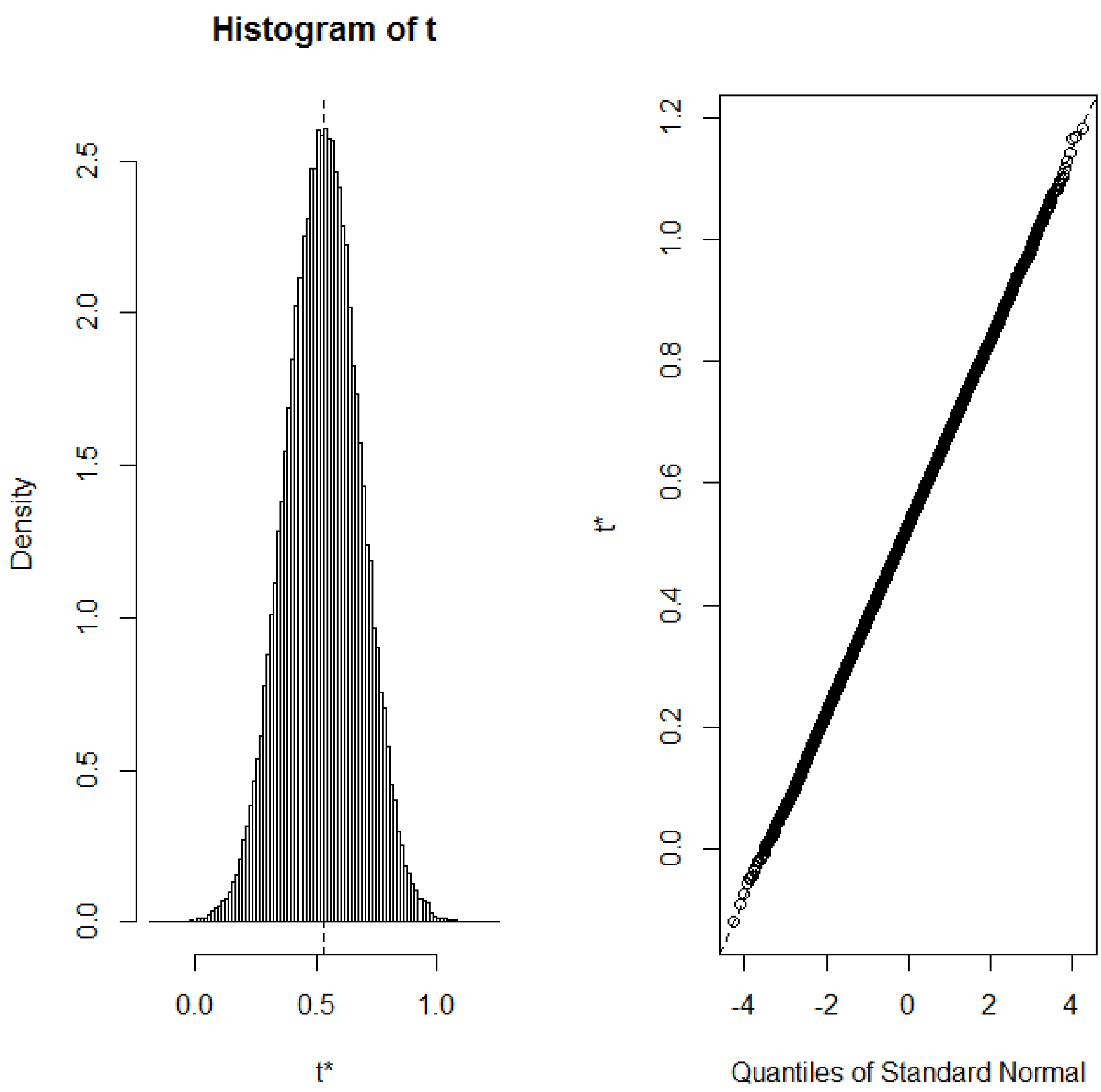


Figure 100. Bootstrapped mean difference for experimental conditions V_{10} vs. V_{11} based on 100000 replicas.

Table 43

Results of Bca bootstrap analysis (experimental condition V_{10} vs. V_{11}).

```
RESULTS OF BCa BOOTSTRAP FOR DIFF.MEAN

   SUMMARY         Pop.1         Pop.2  n Statistic  Observed
STATISTICS dataexp1$v01 dataexp1$v11 82 diff.mean 0.5300037

BOOTSTRAP Replications      Mean        SE     Bias Percent.bias
  SUMMARY       100000 0.5302081 0.1536657 0.000204       0.0385

HYPOTHESIS Null Alternative   P.value
      TEST    0   not-equal P < 0.001

CONFIDENCE Level      Type Confidence.interval
  INTERVAL   95% two-sided    (0.2275, 0.8306)
```

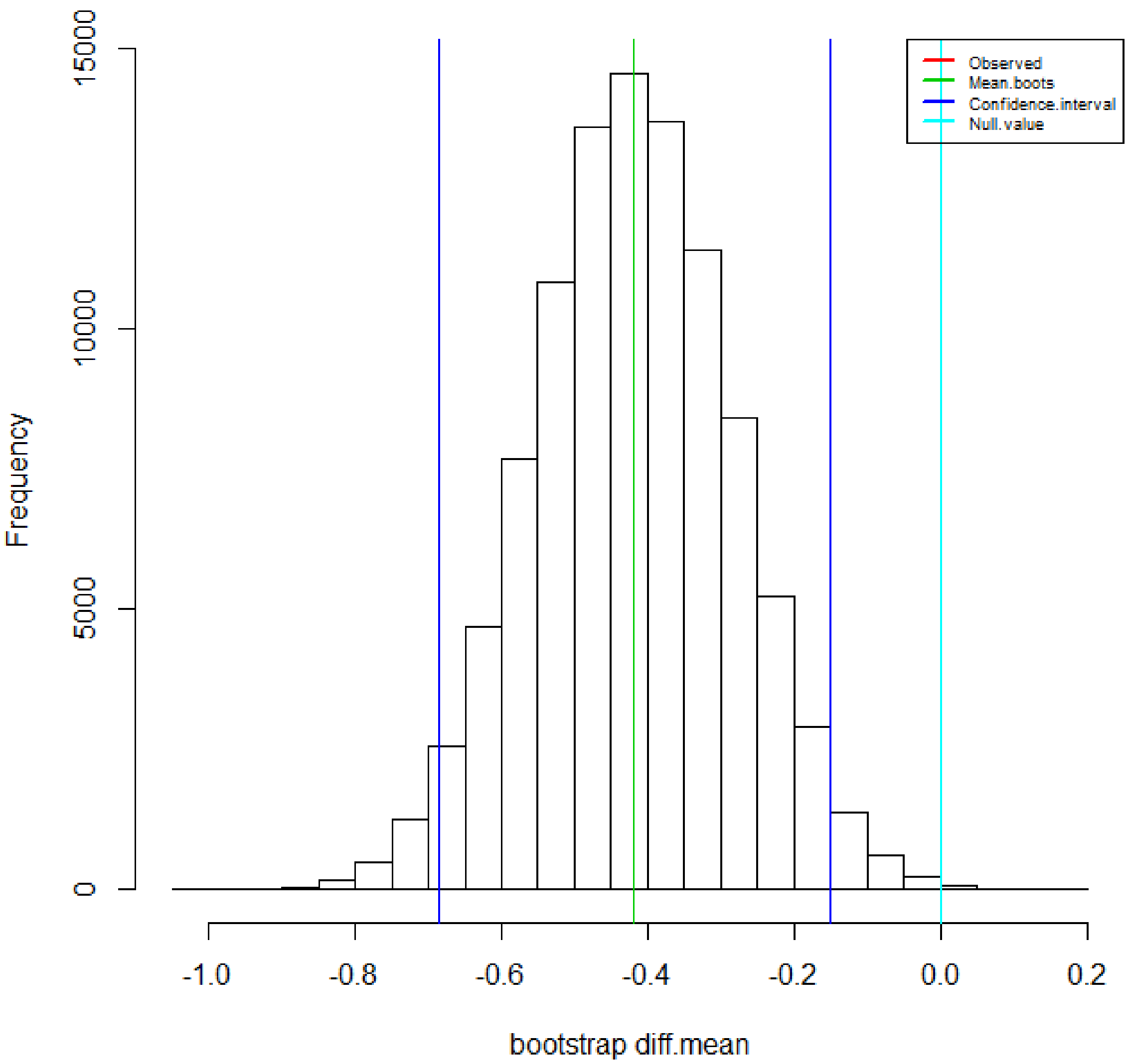


Figure 101. Histogram of the bootstrapped mean difference between experimental condition V_{00} and V_{10} based on 100000 replicates (bias-corrected & accelerated) with associated 95% confidence intervals.

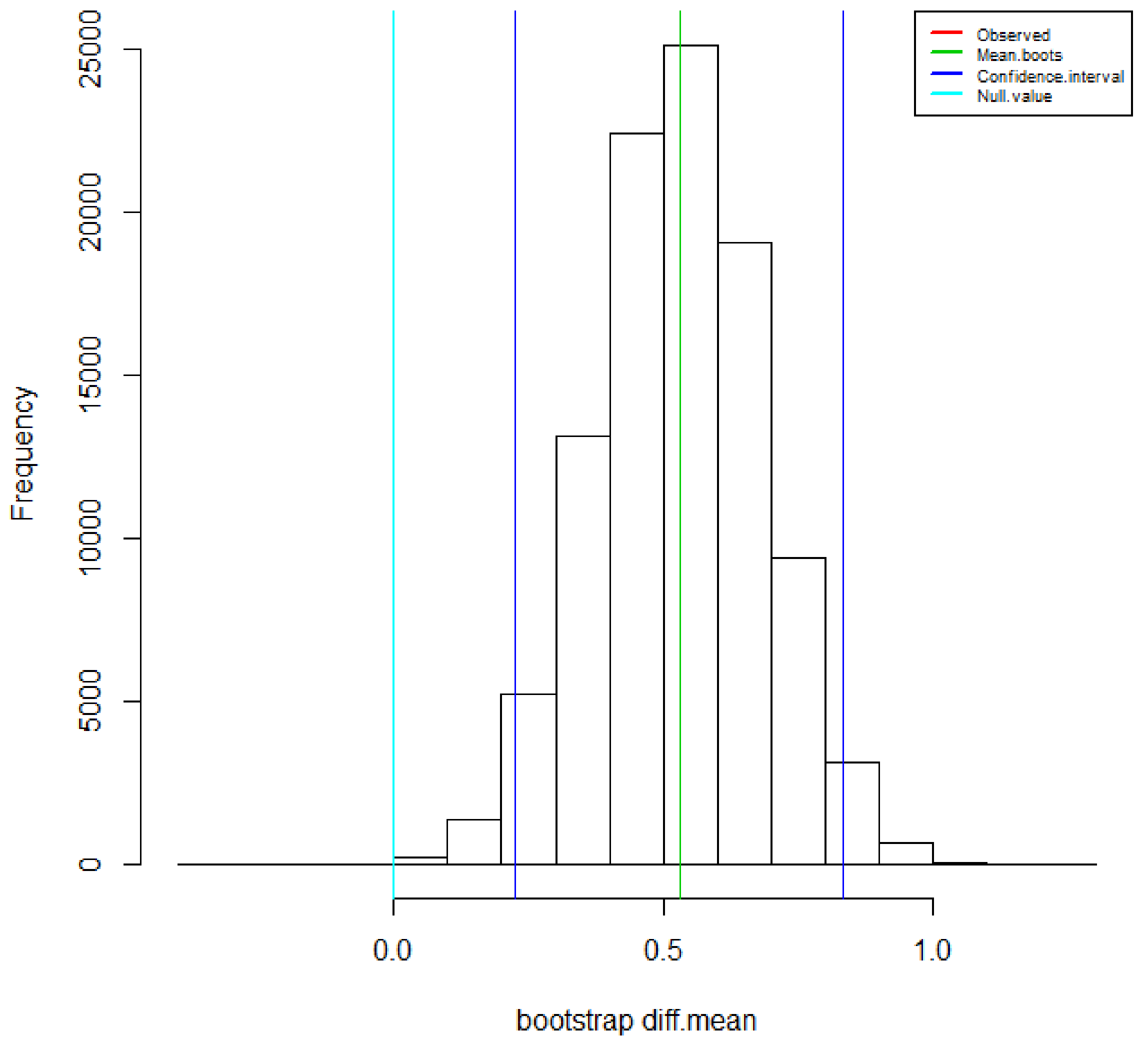


Figure 102. Histogram of the bootstrapped mean difference between experimental condition V_{01} and V_{11} based on 100000 replicates (bias-corrected & accelerated) with associated 95% confidence intervals.

We applied the BCa (bias-corrected & accelerated) bootstrap to the data (Harald Steck & Jaakkola, 2003). Computations are based on R=100000 bootstrap replicates. BCa method for computing bootstrap CIs, which has been shown to have excellent coverage in a wide. For both normal and nonnormal population distributions with sample sizes of roughly 20 or more, Monte Carlo research has shown that BCa intervals yield small coverage errors for means, medians, and variances (Lei & Smith, 2003), correlations (Padilla & Veprinsky, 2012), and Cohen's d (Algina, Keselman, & Penfield, 2006). The magnitude of the coverage errors, and whether they are liberal or conservative, depends on the particular statistic and the population distribution, and BCa intervals can be outperformed by other methods in particular circumstances (Hess, Hogarty, Ferron, & Kromrey, 2007). In sum, the results confirm corroborate the robustness of our previous analyses.

Appendix B16 Bootstrapped effect sizes and 95% confidence intervals

In addition we employed the "`BootES`" package (Kirby & Gerlanc, 2013) in R to bootstrap the confidence intervals of the effect size (i.e, Cohens *d*).

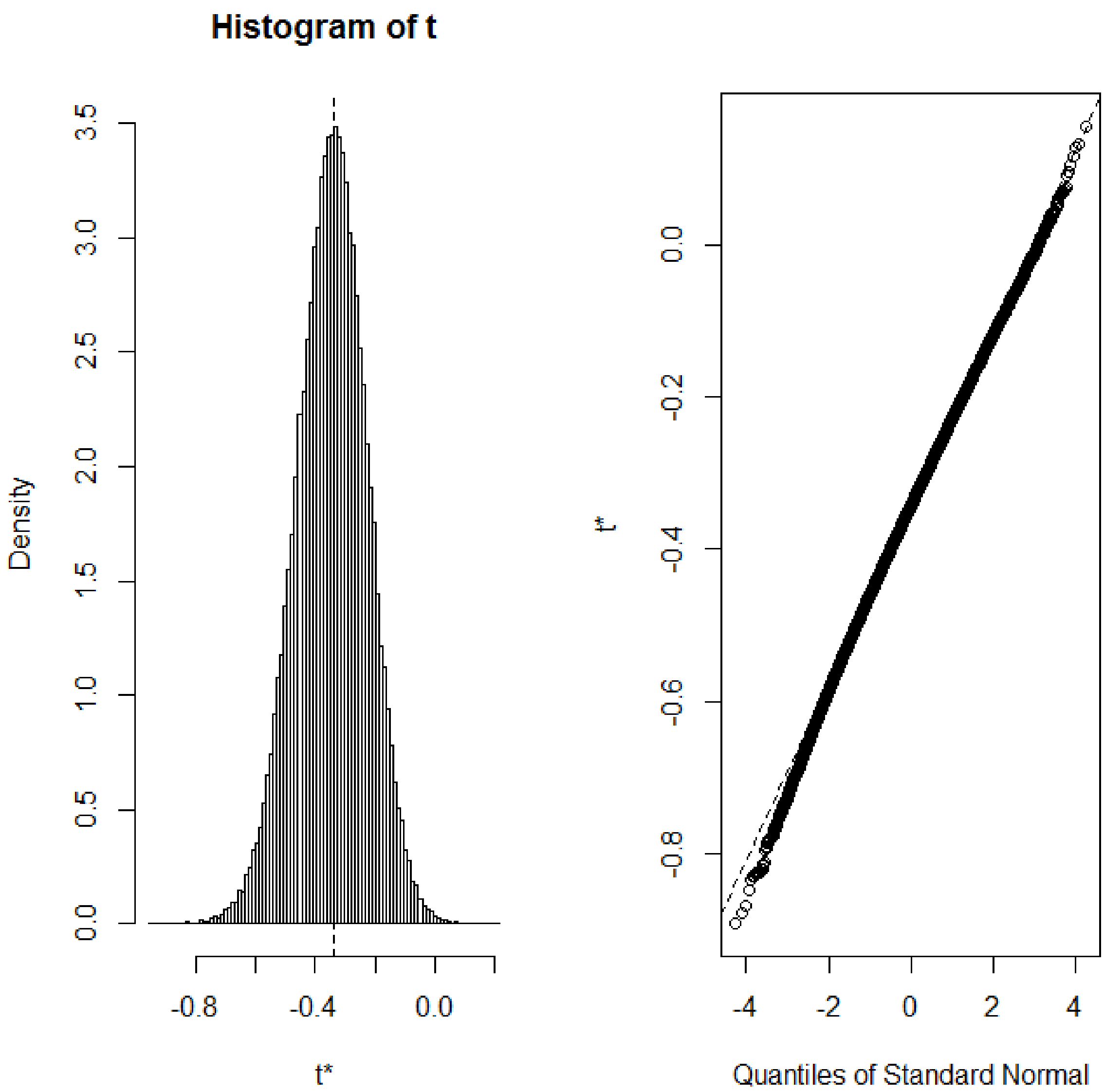


Figure 103. Bootstrapped effect size (Cohen's *d*) for condition V_{00} vs V_{01} based on *R*=100000.

Numerical results:

```
95.00% bca Confidence Interval, 100000 replicates
Stat        CI (Low)    CI (High)   bias        SE
-0.339      -0.566      -0.109      -0.006      0.117
```

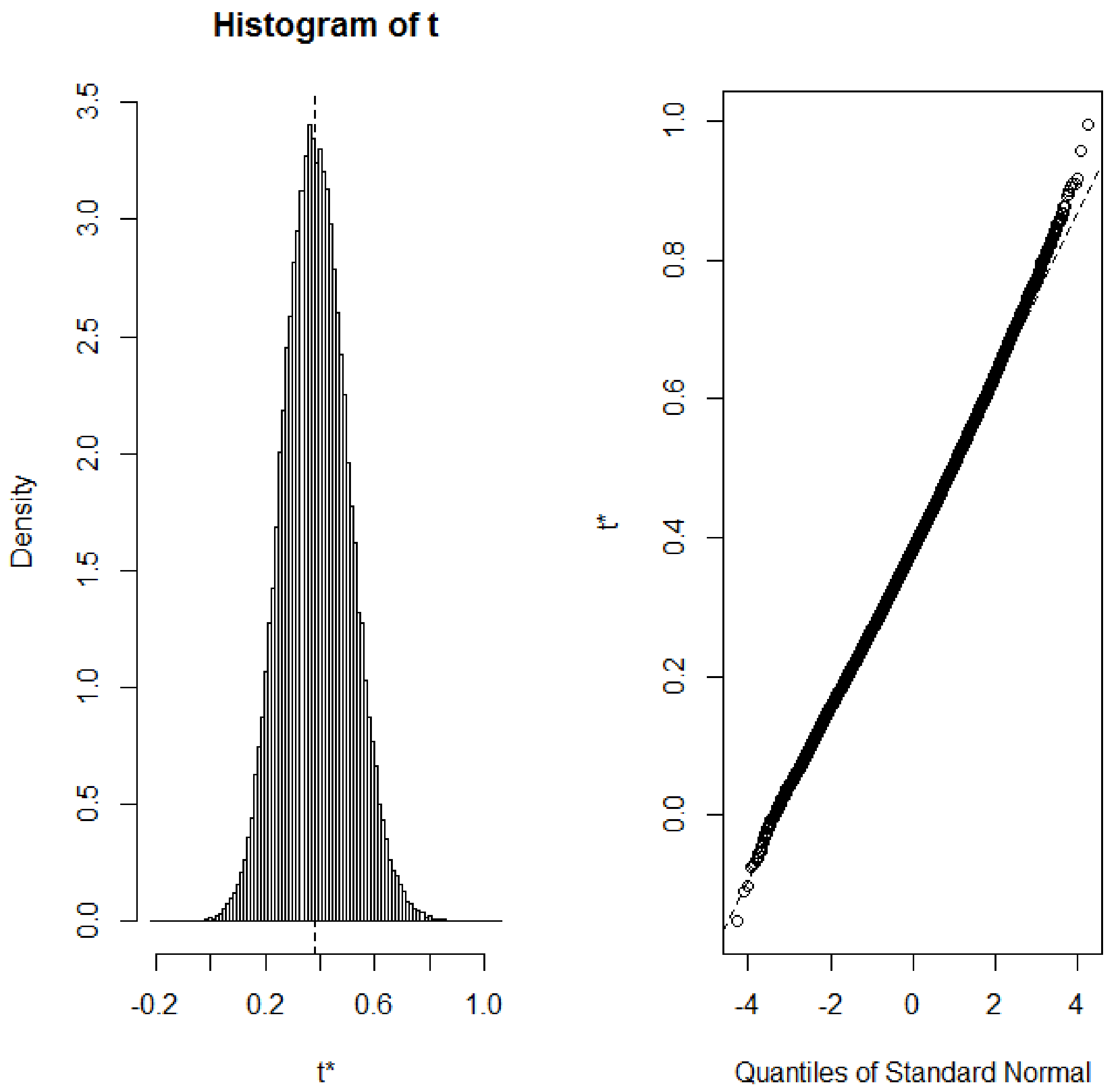


Figure 104. Bootstrapped effect size (Cohen's *d*) for condition V_{10} vs V_{11} based on *R*=100000.

Numerical results:

95.00% bca Confidence Interval, 100000 replicates				
Stat	CI (Low)	CI (High)	bias	SE
0.378	0.141	0.608	0.007	0.120

The bootstraps corroborate the previously reported effect sizes, thereby providing additional evidence for the robustness and stability of the results. The bootstrapped bias corrcted & accelerated 95% confidence intervals provide a higher degree of statistical precision than the previous NHST analysis did (cf. Table 3).

Appendix B17 Bayesian bootstrap

Given the logical shortcomings and ubiquitous misinterpretations associated with NHST confidence intervals (Hoekstra et al., 2014), we performed a Bayesian bootstrap with associated high density intervals (Silverman, 1986). Bayesian high density intervals provides much more detailed information than conventional frequentist confidence intervals do (Kruschke, 2015; Kruschke & Liddell, 2017c) and they are not inherently prone to logical misapprehension. For this analytic purpose, we utilised the "`bayesboot`" package[238] in R which provides an implementation of the Bayesian bootstrap[239] formalised by Rubin (1981). We fixed the size of the posterior sample from the Bayesian bootstrap to 100000 in order to achieve a high degree of statistical accuracy. Moreover, we utilised the implemented "parallel processing" functionality of the "`plyr`" package (Wickham, 2014) in order to boost the speed of the simulations. First, we computed Bayesian bootstraps for means per experimental condition. The density estimates for experimental condition V_{00} and V_{10} are combined in Figure 105 and numerical summery is given in

[238] The "`bayesboot`" package for R can be downloaded from the collaborative GitHub open-source (crowdsourced) software repository (Bååth, 2012) under the following URL: https://github.com/rasmusab/bayesboot Unfortunately, there are currently no naming conventions in R which renders the declaration of variables and functions somewhat arbitrary (cf. Kahneman & Tversky, 1974).

[239] The underlying model can be formalised as follows:

$x_i \leftarrow d_{k_i}\}$ for i in 1..N 1

$k_i \sim \text{Categorical}(\pi)\}$ for i in 1..N 1

$\pi \sim \text{Dirichlet}(0_1, \ldots, 0_K)$

Table 44 and Table 4, respectively.

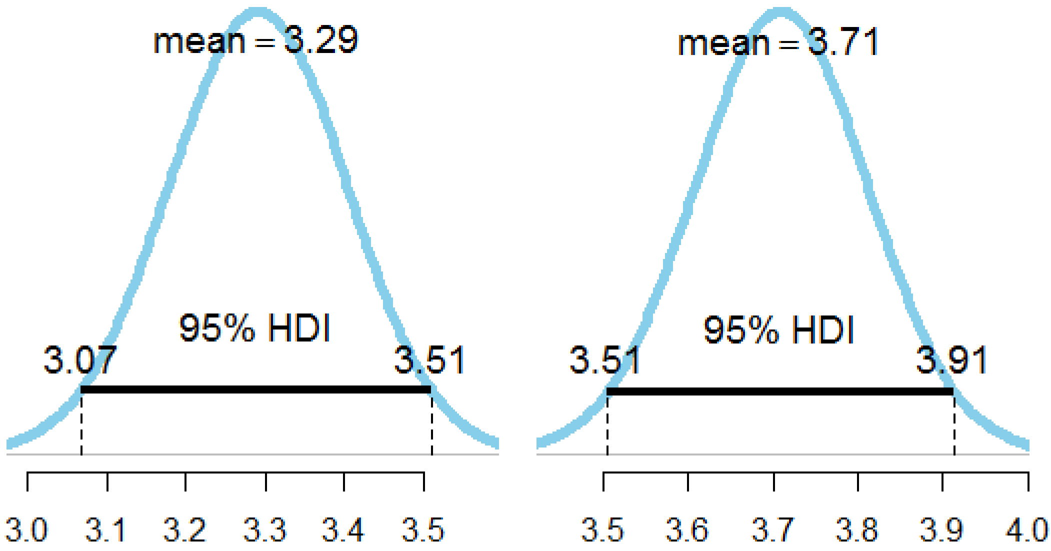


Figure 105. Posterior distributions for experimental conditions V_{00} and V_{10} with associated 95% high density intervals.

Table 44

Numerical summary of Bayesian bootstrap for condition V_{00}.

```
Bayesian bootstrap

Number of posterior draws: 100000

Summary of the posterior (with 95% Highest Density Intervals):
 statistic     mean        sd  hdi.low hdi.high
        V1 3.289989 0.1112057 3.074747 3.510436

Quantiles:
 statistic    q2.5%     q25%   median     q75%   q97.5%
        V1 3.069676 3.215547 3.290817 3.365716 3.505751
```

Table 45

Numerical summary of Bayesian bootstrap for condition V_{10}.

```
Bayesian bootstrap

Number of posterior draws: 100000

Summary of the posterior (with 95% Highest Density Intervals):
 statistic     mean        sd  hdi.low hdi.high
        V1 3.710067 0.1024466 3.511828 3.914148

Quantiles:
 statistic    q2.5%     q25%   median     q75%   q97.5%
        V1 3.507736 3.641826 3.710039 3.778753 3.910511
```

In sum, the results indicate that the Bayesian bootstrapped posterior mean estimate for condition V_{00} is 3.29 with a 95% HDI[240] ranging from [3.07, 3.51]. The bootstrapped posterior mean of condition V_{10} was estimated to be 3.7 with a 95% HDI spanning from [3.51, 3.91]. In contrast to NHST confidence intervals, the HDI indicates that there is a 95% probability that the "true" value of the mean lies within the boundaries of the respective interval (Kruschke & Liddell, 2017b). That is, it can be concluded that there is a 95% probability that the credible mean for condition V_{00} lies between the infimum of 3.07 and the supremum of 3.51. This kind of probabilistic conclusion cannot be derived from classical frequentist confidence intervals — even though they are evidently ubiquitously fallaciously misinterpreted in this way by the majority of academic researchers[241] (Hoekstra et al., 2014).

[240] The HDI summarizes the distribution by specifying an interval that spans most of the distribution, say 95% of it, such that every point inside the interval has higher believability than any point outside the interval. Its high dimension counterpart is HDR (high density region; a region can be n-dimensional whereas an interval is by definition unidimensional). However, in the context at hand, we are primarily concerned with single (one-dimensional) parameters.

[241] Invalid logical conclusions can have large ramification because they necessarily lead to irrational decisions. Ergo, it is pivotal that researchers utilise analytic methods that are not prone to international biases (cf. Ioannidis, 2005). The decisions researchers base on their (il)logical analytical conclusions oftentimes have far reaching real-world consequences and the implications of such cognitive biases should not be taken lightly (Goldstein, 2006).

Next, we conducted Bayesian bootstraps for experimental conditions V_{01} and V_{11}. The results indicate that the bootstrapped posterior mean for condition V_{01} is 7.22 with a 95% HDI ranging from [6.97, 7.47], whereas the mean of condition V_{11} was 6.69 with a 95% HDI spanning from [6.45, 3.92].

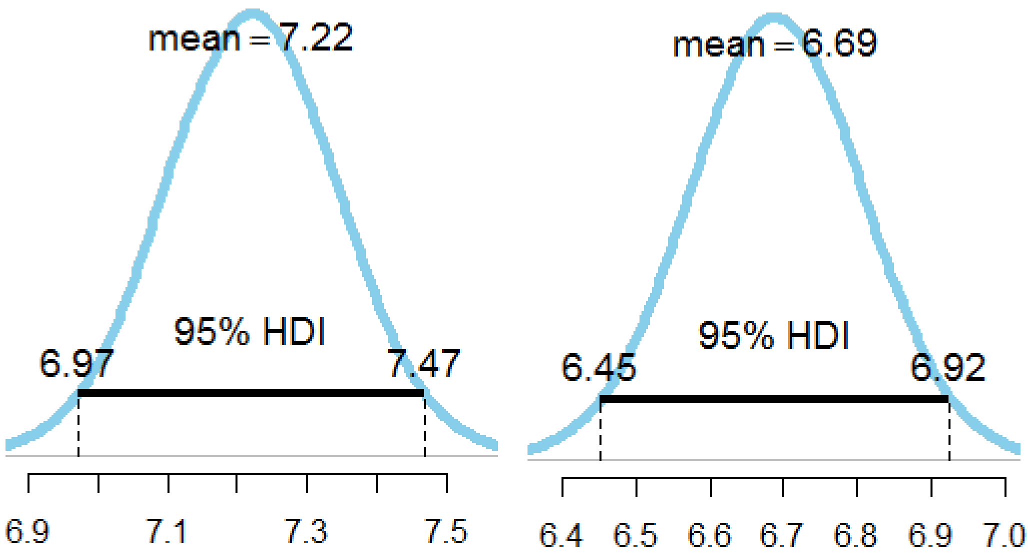


Figure 106. Posterior distributions (based on 100000 posterior draws) for experimental conditions V_{01} and V_{11} with associated 95% high density intervals.

Table 46

Numerical summary of Bayesian bootstrap for condition V_{01}.

```
Bayesian bootstrap

Number of posterior draws: 100000

Summary of the posterior (with 95% Highest Density Intervals):
 statistic     mean        sd  hdi.low hdi.high
        V1 7.220364 0.1243281 6.975719 7.465398

Quantiles:
 statistic    q2.5%     q25%   median     q75%   q97.5%
        V1 6.974948 7.136895 7.220442 7.303612 7.464896
```

Table 47

Numerical summary of Bayesian bootstrap for condition V_{11}.

```
Bayesian bootstrap

Number of posterior draws: 100000

Summary of the posterior (with 95% Highest Density Intervals):
 statistic     mean        sd  hdi.low hdi.high
        V1 6.690185 0.1178996 6.458225 6.921827

Quantiles:
 statistic    q2.5%     q25%   median     q75%   q97.5%
        V1 6.457083 6.611789 6.690431 6.769331 6.920817
```

Finally, we computed Bayesian bootstraps for the mean difference between condition in order to explicitly evaluate our *a priori* hypotheses. The density estimates of the first analysis, comparing conditions V_{00} vs. V_{10}, are visualised in

Figure 107 and a histogram of the posterior distribution is provided in

Figure 108. Posterior distribution (n=100000) of the mean difference between V00 vs. V10.

In addition, a numerical summary is given in

Table 48. From this analysis it can be concluded that the mean difference between experimental condition V_{00} vs. V_{10} is ≈-0.42with a 95% HDI spanning from [-0.72, -0.12]. In other terms, there is a 95% probability that the credible value of the mean lies between -0.72 and -0.12. Furthermore, it can be concluded that the estimated probability that the mean difference between experimental condition V_{01} vs. V_{11} is < 0 is exactly 0.9975012. In addition, we construted a region of practical equivalence (ROPE) around the comparison value of zero (referring to H_0). In

Figure 107, the comparison value is shown as a vertical green dashed line and the ROPE is demarcated by red vertical dashed lines. Prima vista, it can be seen that the probability mass within the ROPE is 2% and that the probability mass above and below the comparison value is 99.7% < 0 < 0.3. Given that the ROPE lies entirely outside the HDI, H_0 can be rejected (Kruschke, 2014).

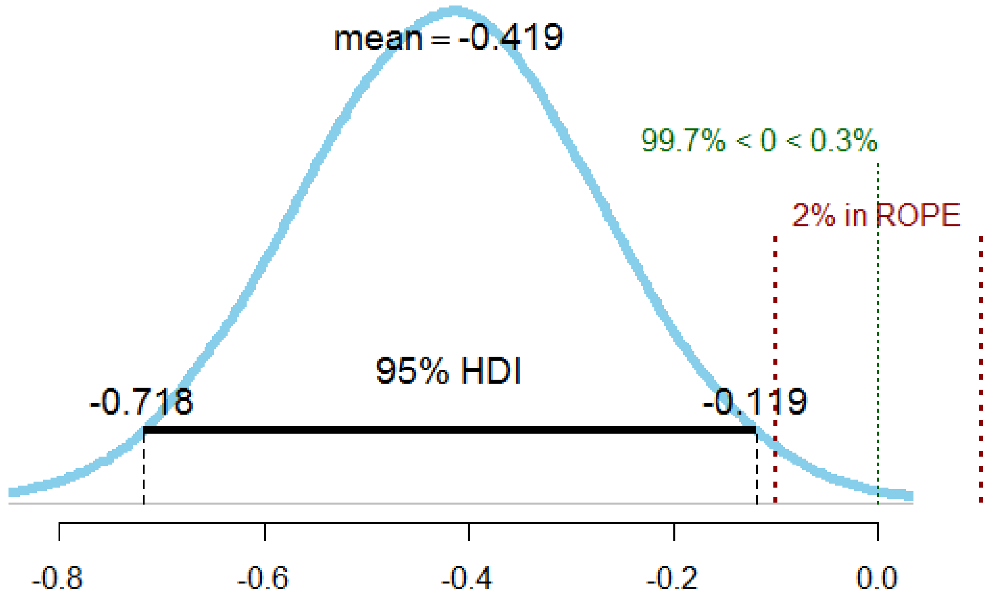


Figure 107. Histogram of the Bayesian bootstrap (R=100000) for condition V_{00} vs. V_{10} with 95% HDI and prespecified ROPE ranging from [-0.1, 0.1].

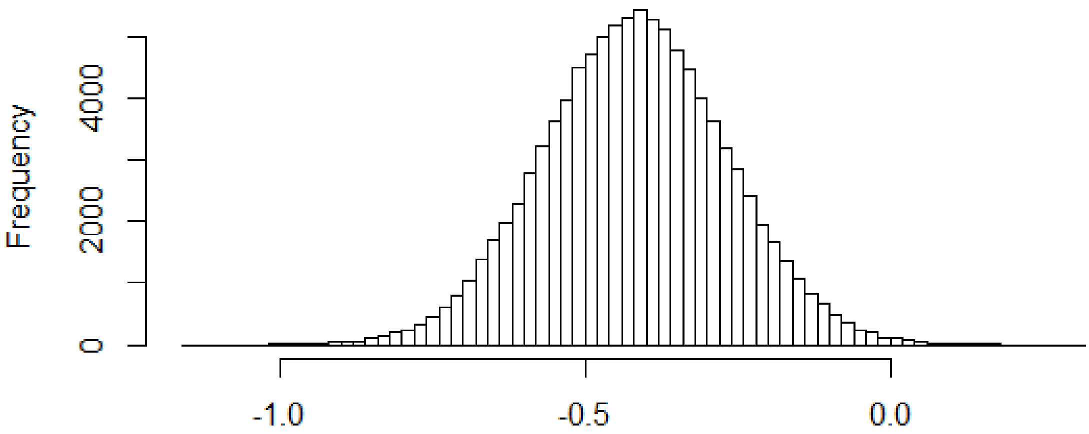


Figure 108. Posterior distribution (n=100000) of the mean difference between V_{00} vs. V_{10}.

Table 48

Numerical summary of Bayesian bootstrap for the mean difference between V_{00} vs. V_{10}.

```
Bayesian bootstrap

Number of posterior draws: 100000

Summary of the posterior (with 95% Highest Density Intervals):
 statistic       mean       sd   hdi.low   hdi.high
        V1 -0.4192176 0.150902 -0.715011 -0.1240525

Quantiles:
 statistic      q2.5%        q25%    median       q75%      q97.5%
        V1 -0.7137307 -0.5201843 -0.418764 -0.3184508 -0.1223835
```

We repeated the same analysis for the mean difference between experimental condition V_{01} vs. V_{11}. A visual synopsis is given in Figure 109. The associated posterior distribution is plotted in Figure 109.

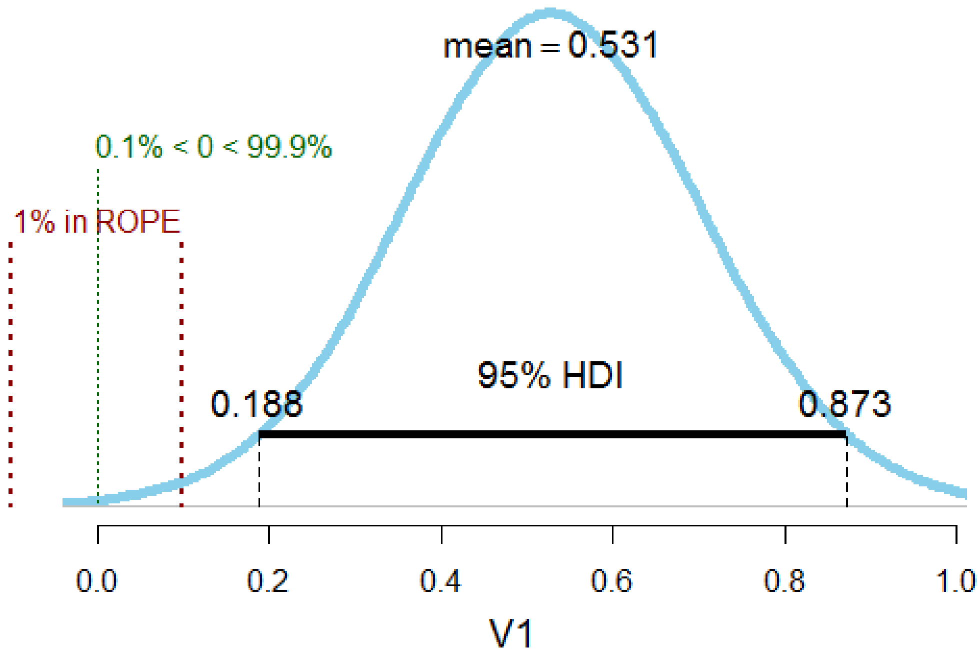


Figure 109. Histogram of the Bayesian bootstrap (R=100000) for condition V_{01} vs. V_{11} with 95% HDI and prespecified ROPE ranging from [-0.1, 0.1].

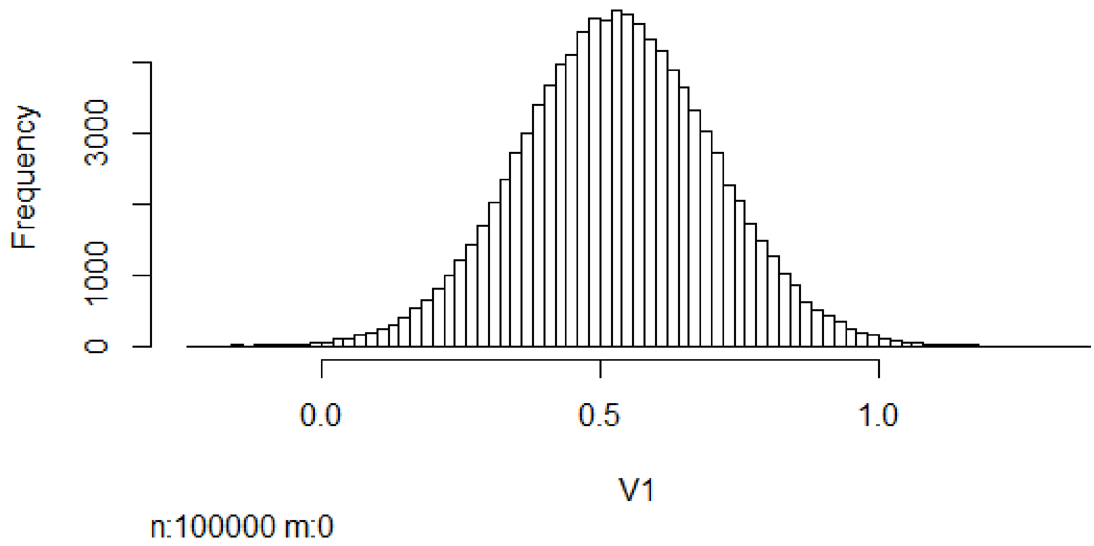


Figure 110. Posterior distribution (n=100000) of the mean difference between V_{01} vs. V_{11}.

Table 49

Numerical summary of Bayesian bootstrap for the mean difference between V_{00} vs. V_{10}.

```
Bayesian bootstrap

Number of posterior draws: 100000

Summary of the posterior (with 95% Highest Density Intervals):
 statistic      mean        sd   hdi.low hdi.high
        V1 0.5306958 0.1718346 0.1927101 0.867818

Quantiles:
 statistic   q2.5%      q25%    median      q75%    q97.5%
        V1 0.19361 0.4148349 0.5301679 0.6456821 0.8691314
```

The probability that the mean difference between experimental condition V_{01} vs. V_{11} is > 0 is exactly 0.99907.

In sum, the Bayesian bootstrap corroborated the conclusions derived from the results of our initial frequentist analysis and provided additional new information which was unavailable in the NHST framework. The analysis provided a methodological cross-validation and confirmed the robustness of our results. Moreover, the Bayesian bootstrap approach allowed us to compute 95% high density intervals which were utilised in combination with ROPEs to test our hypotheses. The results of the Bayesian bootstrap converged with those of the classical parametric bootstrap. This is generally the case with large samples and the results of the parametric bootstrap can thus be interpreted in a Bayesian framework if *n* is sufficiently large (with smaller samples the results generally diverge). However, it should be noted that the Bayesian bootstrap (and the classical non-parametric bootstrap) make some assumptions which are questionable and not necessarily appropriate. For instance, it is assumed:

- That values not observed before are impossible
- That values outside the range of the empirical data are impossible

It has been asked before: "…is it reasonable to use a model specification that effectively assumes all possible distinct values of X have been observed?" (D. B. Rubin, 1981).

Appendix B18 Probability Plot Correlation Coefficient (PPCC)

Summary of the results of the "Probability Plot Correlation Coefficient" test (Looney & Gulledge, 1985) using the "`PPCC`"[242] R package. The PPCC computes a goodness-of-fit index $\hat{r}$ for various distributions (Hanson & Wolf, 1996). Hence, it can be utilised to evaluate normal and non-normal distributional hypotheses. Each PPCC test was performed with 10000 Monte-Carlo simulations. The results indicated Gaussianity for all conditions. The PPCC is mathematically defined as the product moment correlation coefficient between the ordered data $x_{(i)}$ and the order statistics medians M_i, whereas the ordered statistic medians are related to the quantile function of the standard normal distribution, $M_i = \phi^{-1}(m_i)$.

Equation 20. Probability Plot Correlation Coefficient (PPCC)

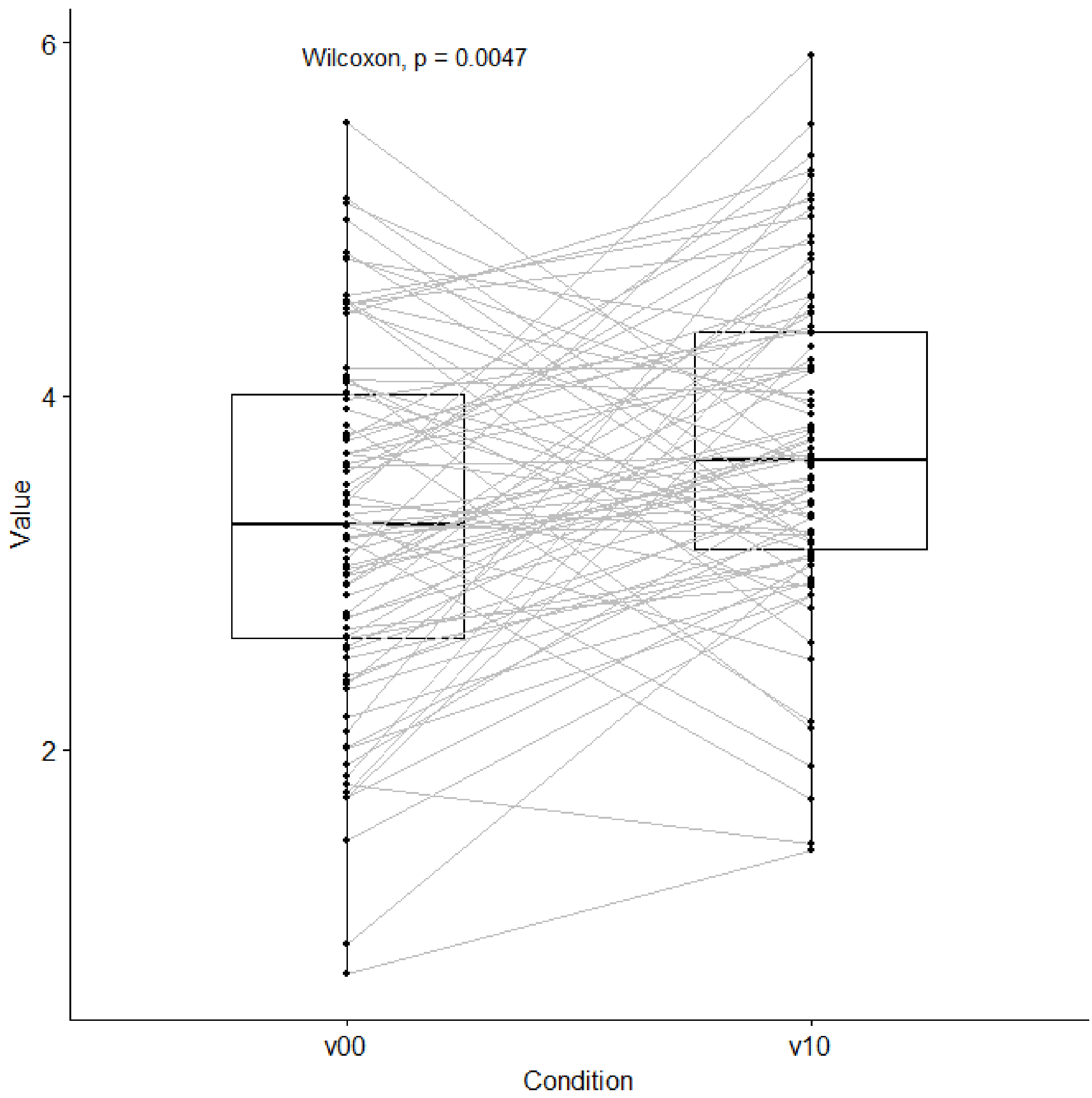
$$r = \frac{\sum_{i=1}^{n} \left(x_{(i)} - \bar{x}\right) \sim (M_i - \bar{M})}{\sqrt{\sum_{i=1}^{n} \left(x_{(i)} - \bar{x}\right)^2 \sim \sum_{j=1}^{n} \left(M_j - \bar{M}\right)^2}},$$

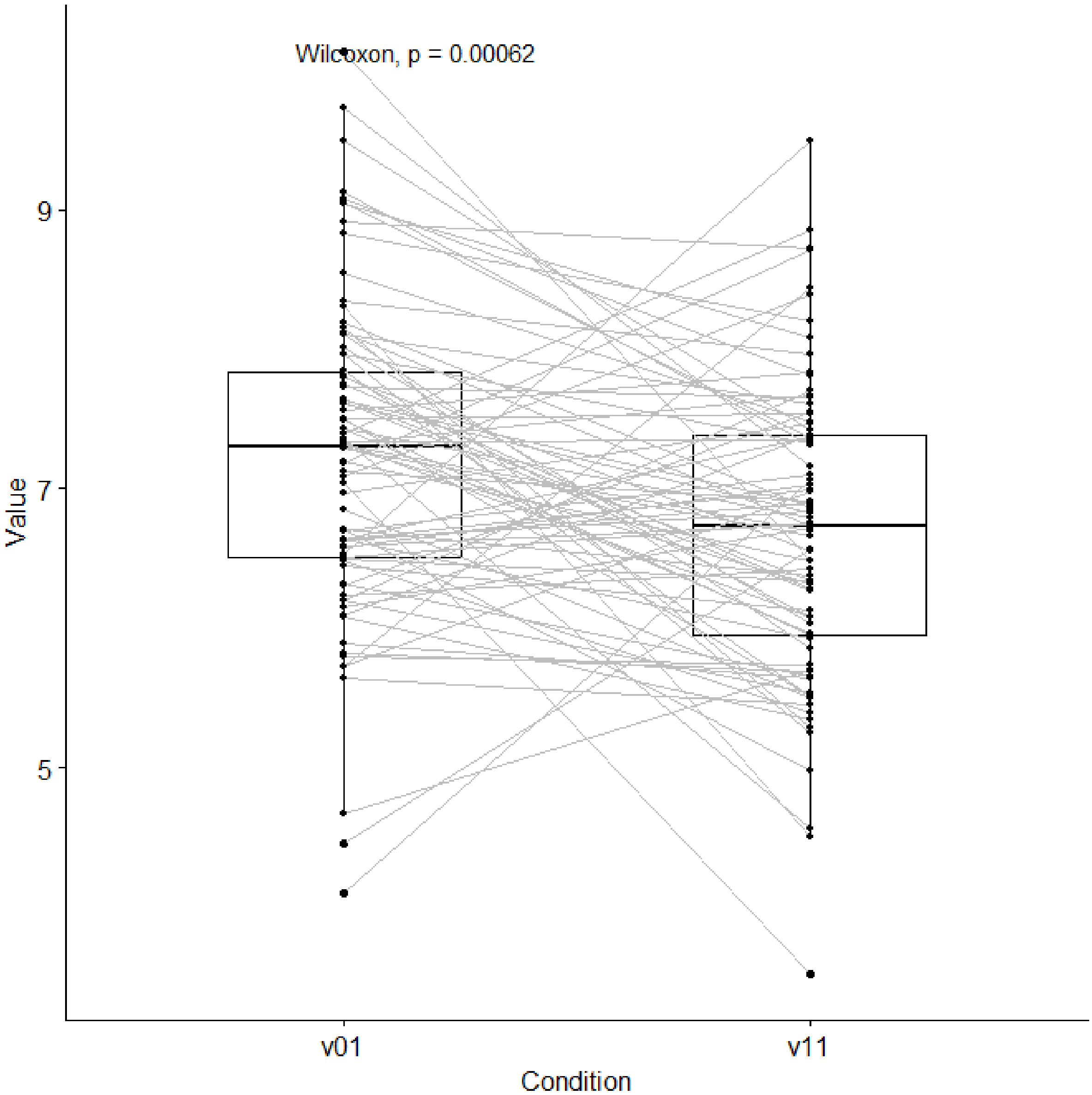
[242] Available on CRAN: https://cran.r-project.org/web/packages/ppcc/ppcc.pdf

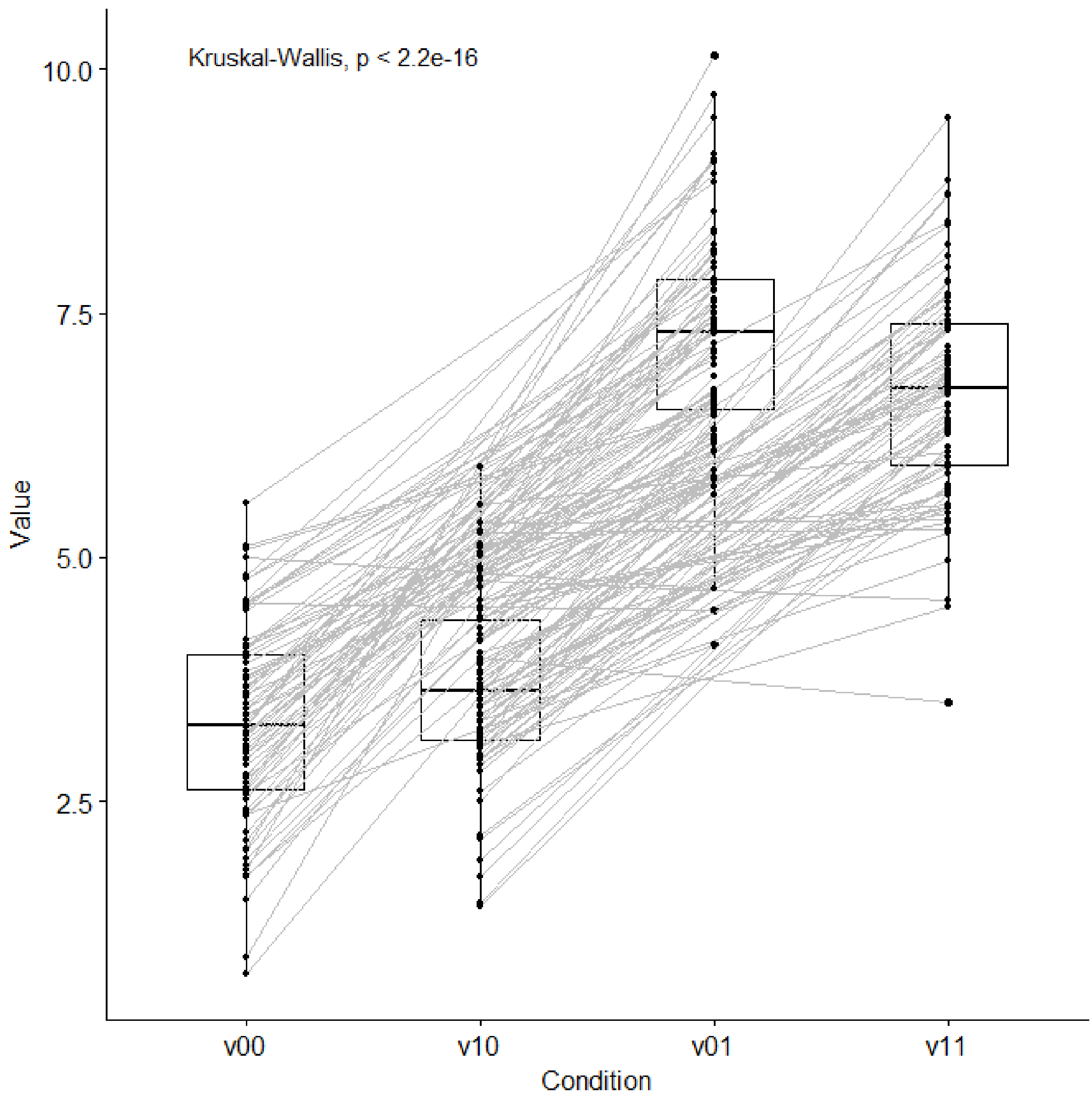
Table 50

Results of PPCC analysis (based on 10000 Monte-Carlo simulations).

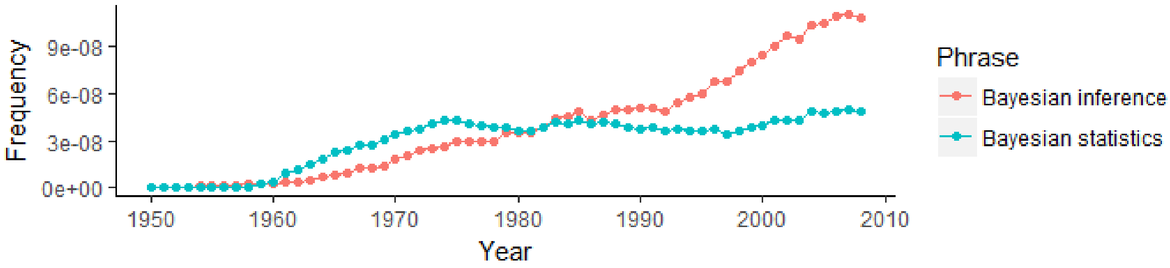
data: dataexp1$v00 ppcc = 0.9966, n = 82, p-value = 0.9091 alternative hypothesis: dataexp1$v00 differs from a Normal distribution
data: dataexp1$v01 ppcc = 0.99195, n = 82, p-value = 0.3399 alternative hypothesis: dataexp1$v01 differs from a Normal distribution
data: dataexp1$v10 ppcc = 0.99319, n = 82, p-value = 0.4643 alternative hypothesis: dataexp1$v10 differs from a Normal distribution
data: dataexp1$v11 ppcc = 0.99557, n = 82, p-value = 0.7864 alternative hypothesis: dataexp1$v11 differs from a Normal distribution

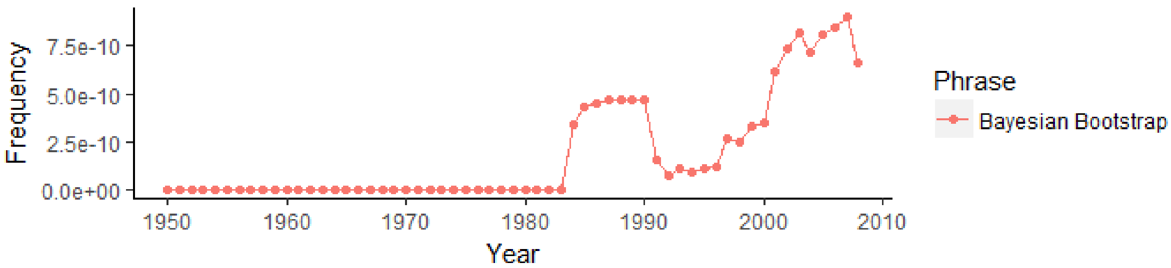

Wilcoxon, p = 0.0047
6
4
2
Value
v00
v10
Condition

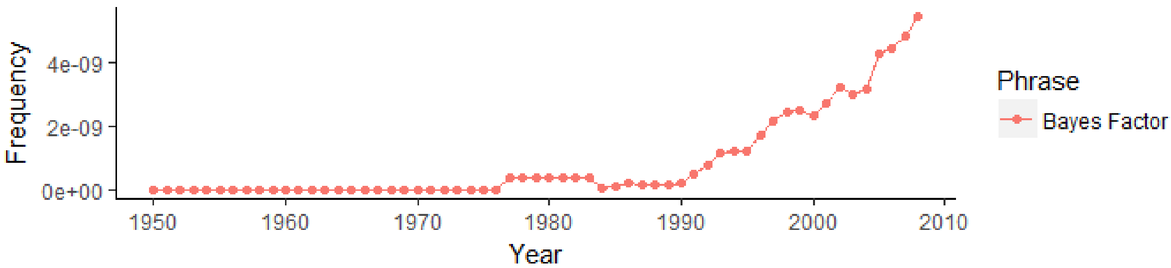

Wilcoxon, p = 0.00062
9
7
5
Value
v01
v11
Condition

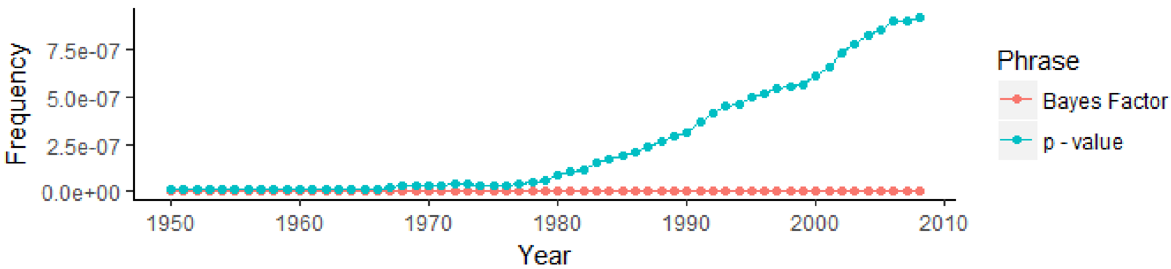

Kruskal-Wallis, p < 2.2e-16
10.0
7.5
5.0
2.5
Value
v00
v10
v01
v11
Condition

Appendix B19 Ngrams for various statistical methodologies









Appendix B20 Bayes Factor analysis (supplementary materials)

In physics the Cauchy distribution (CD) is also termed Lorentz or Breit-Wigner distribution, and it has many applications in particle physics. Cauchy distribution is a *t* distribution with 1 degree of freedom and due to its shape (it belongs to the class of heavy-tailed distribution, see Figure 111 below) it has no determinable mean and an infinite variance (Rouder et al., 2009). Hence it is also called a “pathological" distribution. It has been pointed out that Bayes factors with the Cauchy prior are slightly biased towards H_0 (Rouder et al., 2009), i.e., the Cauchy prior is slightly conservative towards H_1.

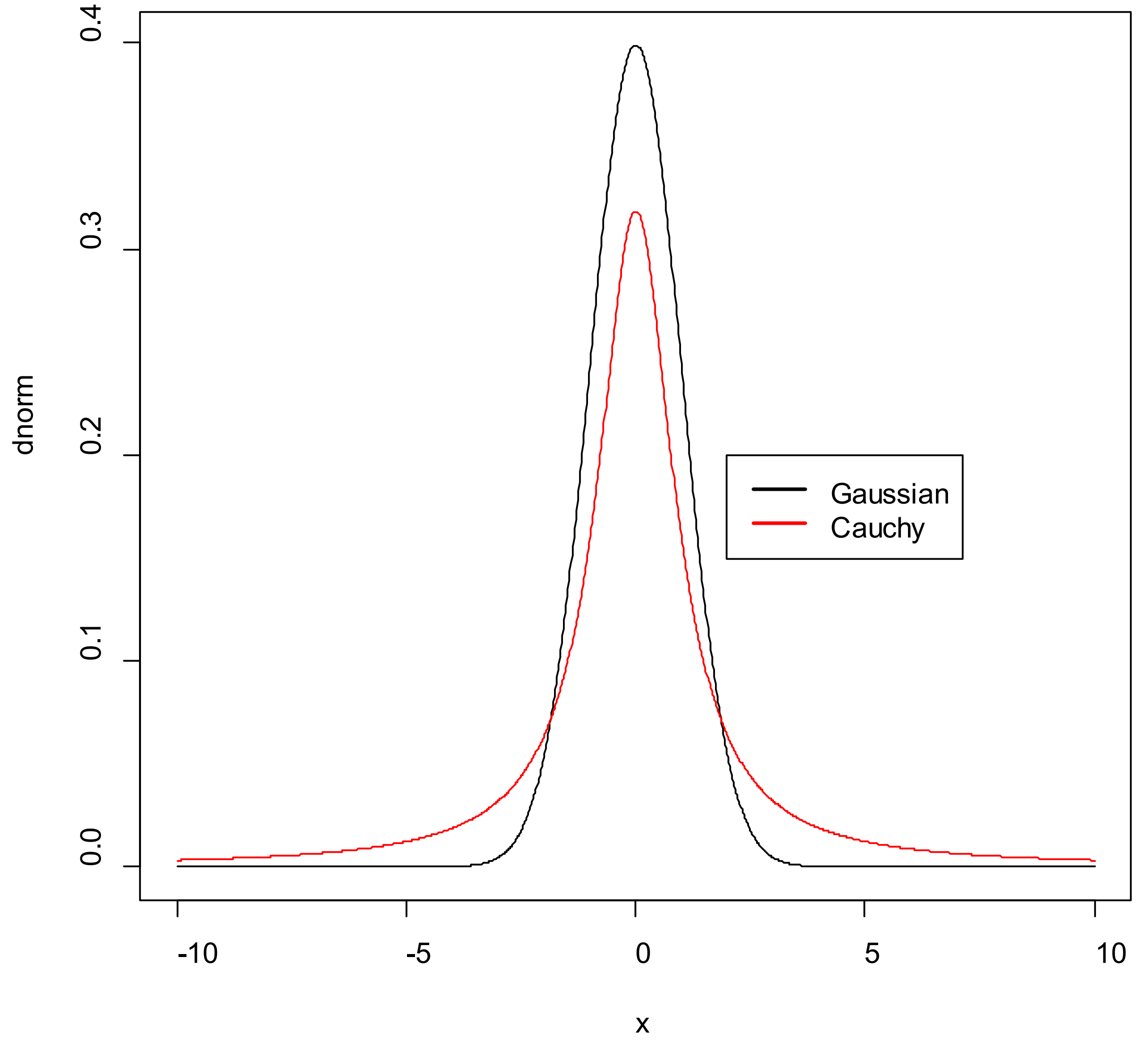


Figure 111. Visual comparison of Cauchy versus Gaussian prior distributions symmetrically centred around δ. The abscissa is standard deviation and ordinate is the density.

```
plot(dnorm, -10, 10, n=1000)

plot(dcauchy, -10, 10, n=1000, col='red', add=TRUE)

legend(0.01,0.01, c("Gaussian","Cauchy"),

  lty=c(1,1,1),

  lwd=c(2,2,2), col=c("black", "red"))
```

Code 6. R code for plotting Cauchy versus Gaussian distribution (n=1000)

symmetrically centred around δ [-10,10].

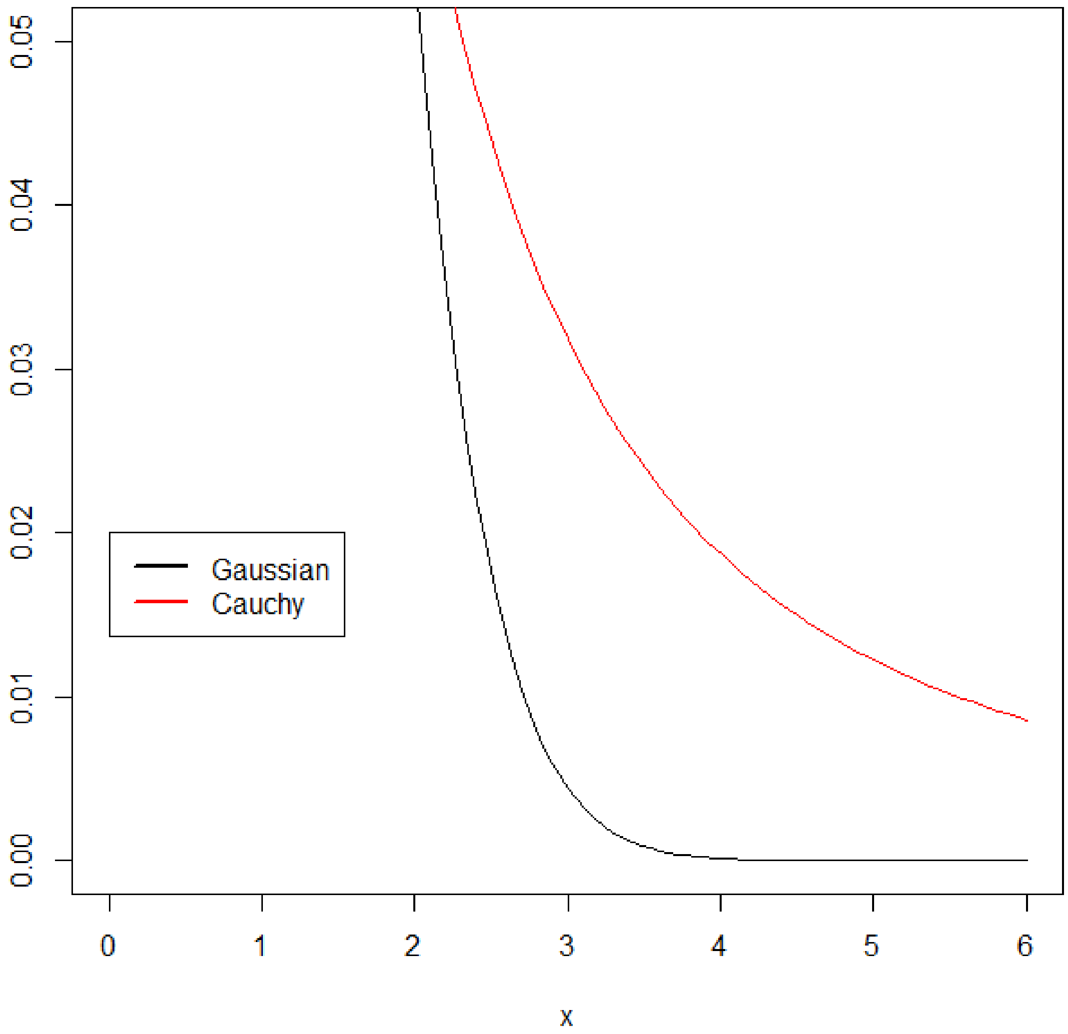


Figure 112. Graphic of Gaussian versus (heavy tailed) Cauchy distribution. X axis is standard deviation and y axis is the density

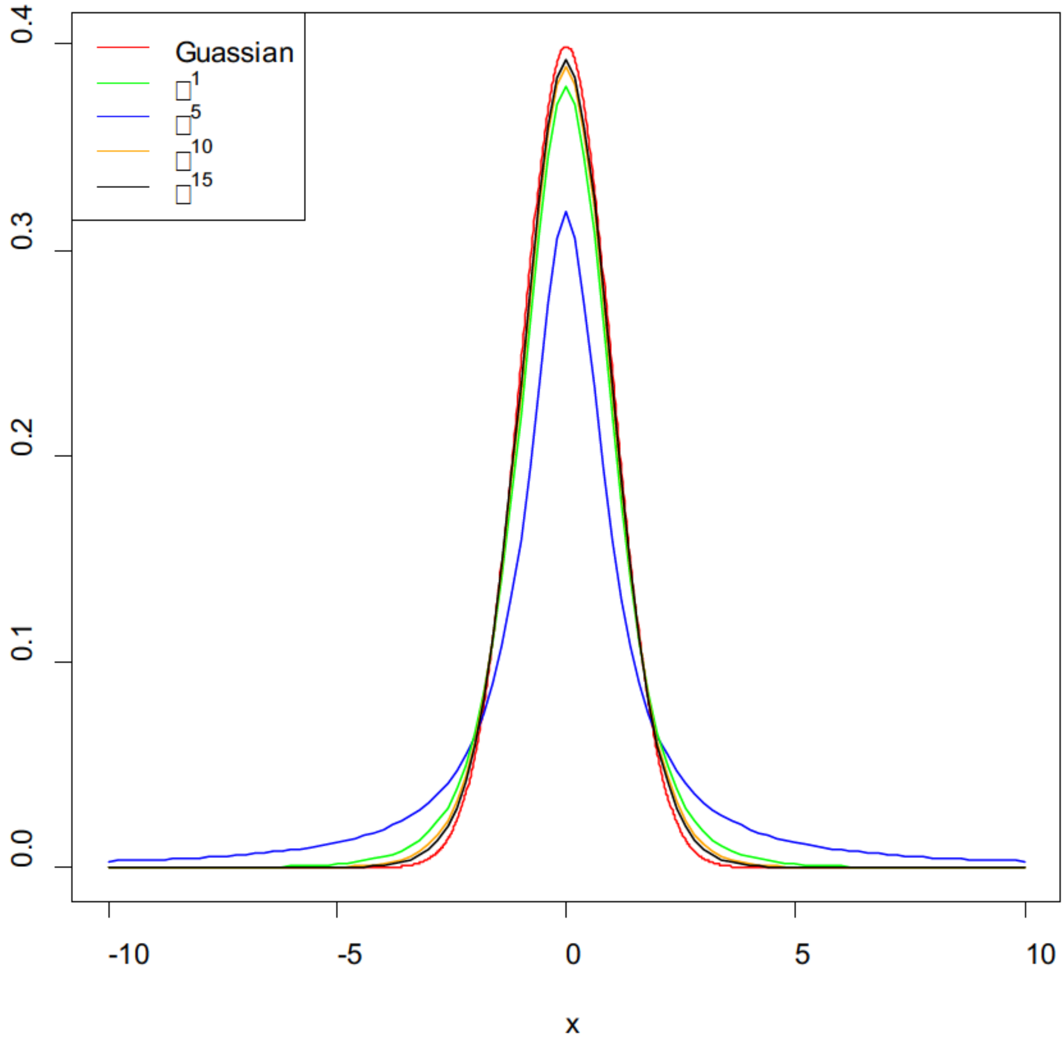
```r
low <- 0; high <- 6
curve(dnorm,from = low, to = high, ylim = c(0, .05), col = "blue", ylab = "
", add = FALSE)
curve(dcauchy,from = low, to = high, col = "red", add = TRUE)
plot(dnorm, -10, 10, n=1000)
plot(dcauchy, -10, 10, n=1000, col='red', add=TRUE)
legend(0,0.02, c("Gaussian","Cauchy"),
  lty=c(1,1,1), # symbols (lines)
  lwd=c(2,2,2), col=c("black", "red"))
legend(0,0.03, c("Gaussian","Cauchy"),
  lty=c(1,1,1), # symbols (lines)
  lwd=c(2,2,2), col=c("blue", "red"))
```

Code 7. R code for plotting tails of Cauchy versus Gaussian distributions.

The Cauchy distribution is a t distribution with a single degree of freedom. It has tails so heavy that neither its mean nor its variance exist. A comparison of the Cauchy prior to the unit-information prior is shown in Figure 3B. As can be seen, the Cauchy allows for more mass on large effects than the standard normal. Consequently, Bayes factors with the Cauchy prior favour the null a bit more than those with the unit-information prior. The JZS prior is designed to minimize assumptions about the range of effect size, and in this sense it is an objective prior. Smaller values of r, say 0.5, may be appropriate when small effect sizes are expected a priori; larger values of r are appropriate when large effect sizes are expected. The choice of r may be affected by theoretical considerations, as well: Smaller values are appropriate when small differences are of theoretical importance, whereas larger values are appropriate when small differences most likely reflect nuisances and are of little theoretical importance. In all cases, the value of r should be chosen prior to analysis and without influence from the data. In summary, r 5 1.0 is recommended (serves as a benchmark) - surreptitiously choosing a self-serving prior - This appearance is deceiving. Bayes factors are not particularly sensitive to reasonable variation in priors, at least not with moderate sample sizes. (Berger & Berry, 1988)

It is reasonable to ask whether hypothesis testing is always necessary. In many ways, hypothesis testing has been employed in experimental psychology too often and too hastily, without sufficient attention to what may be learned by exploratory examination for structure in data (Tukey, 1977). To observe structure, it is often sufficient to plot estimates of appropriate quantities along with measures of estimation error (Rouder & Morey, 2005). As a rule of thumb, hypothesis testing should be reserved for those cases in which the researcher will entertain the null as theoretically interesting and plausible, at least approximately. Researchers willing to perform hypothesis testing must realize that the endeavor is inherently subjective and objectivity is illusionary, (as might be the objectivity of science in general as argued by) (Irwin & Real, 2010). Moreover; similar unconscious biases as those observed in legal decision making might apply (but see Molloy, 2011)

Appendix B21 T-distribution with varying ν parametrisation



```
#t distribution with varying nu parametrisation

curve(dnorm(x), -10, 10, n=1000, col = "red", ylab="")

curve(dt(x, df = 1), col = "blue", add = TRUE)

curve(dt(x, df = 5), col = "green", add = TRUE)

curve(dt(x, df = 10), col = "orange", add = TRUE)

curve(dt(x, df = 15), col = "black", add = TRUE)

legend_texts = expression(

   Guassian, nu^1, nu^5, nu^10, nu^15)

legend("topleft",legend = legend_texts, col = c("red", "green", "blue",

"orange", "black"), lty = c(1))
```

Code 8. R code for plotting *t*-distributions with varying ν parametrisation.

In R, the density of *t* at *x* is determined by dt(x,df), where df is the parameter for the degrees of freedom. Note, that the degrees of freedom are not related to a sampling distribution. Here df is not restricted to being an integer (Kruschke, 2010a).

Appendix B22 Evaluation of null-hypotheses in a Bayesian framework: A ROPE and HDI-based decision algorithm

In the majority of psychological research is it is conventional to try to reject H_0. Bayesian parameter estimation can likewise be utilised to assess the credibility of a given null hypotheses (e.g., $\mu_1 - \mu_2 = 0$). This can be achieved by examining the posterior distribution of the plausible parameter values (i.e., one simply checks if the null value lies within the credible interval of θ). If the null value departs from the most credible parameter value estimates it can be rejected in the classical Popperian sense (Meehl, 1967; Rozeboom, 2005; Steiger, 2004). By contrast, if the credible values are almost identical to the null value than H_0 can also be accepted, in contrast to the asymmetry inherent to NHST. To be more explicit, Bayesian parameter estimation methods allow the researcher to accept *and* reject a null value. Hence it can be regarded as a symmetrical hypothesis testing procedure.

Another significant logical problem associated with NHST is that alternative theories can be expressed very imprecisely (if at all) and still be “corroborated” by rejection of H_0. A problem known in philosophy of science as “Meehls’ paradox” (Carlin, Louis, & Carlin, 2009), named after the ingenious psychologist and former APA president Paul Meehl (see Rozeboom, 2005; Steiger, 2004). Differences of means that are infinitesimally larger than zero can become statistically significant if *n* is large enough. That is, given a large enough sample, any magnitude of difference can be considered statistically significantly greater than zero. Bayesian parameter estimation provides methods to circumvent this particular issue by constructing a *region of practical equivalence* (ROPE) around the null value (or any other parameter of interest). The ROPE is a bipolar interval that specifies a predefined range of parameter values that are regarded as compatible with H_0. In other words, the definition of the ROPE depends on the experiment at hand and it involves a subjective judgment on the part of the investigator. As $n \rightarrow \infty$, the probability that the difference of means is exactly zero is zero. Of theoretical interest is the probability that the difference may be too small to be of any *practical significance*. In Bayesian estimation and decision theory, a region of practical equivalence around zero is predefined. This allowed to compute the exact probability that the true value of the difference lies inside this predefined interval (Gelman et al., 2004). In the psychophysics experiment at hand, a difference of ± 0.01 in the visual analogue scale ratings was considered too trivial to be of any theoretical importance (ergo, the *a priori* specified ROPE ranged from [-0.01;0,01]).

In addition to parameter estimation, the posterior distribution can be utilised to make discrete decisions about specific hypotheses. High Density Intervals contain rich distributional information about parameters of interest. Moreover, a HDI can be utilised to facilitate reasonable decisions about null values (i.e., the null hypothesis that there is no difference between condition V_{00} and V_{01}). HDIs indicate which values of θ are most credible/believable. Furthermore, the HDI width conveys information regarding the certainty of beliefs in the parameter estimate, i.e., it quantifies certainty vs. uncertainty. A wide HDI is signifies a large degree of uncertainty pertaining to the possible range of values of θ, whereas a narrow HDI indicates a high degree of certainty with regards to the credibility of the parameters in the distribution. It follows, that the analyst can define a specific degree of certainty by varying the width of the HDI. In other words, the HDI entails the assembly of most likely values of the estimated parameters. For instance, for a 95% HDI, all parameter values inside the interval (i.e., 95% of the total probability mass) have a higher probability density (i.e., credibility/trustworthiness) relative to those outside the interval (5% of the total mass). Moreover, the HDI contains valuable distributional information, I n contrast to classic frequentists confidence intervals (CI). For a classical 95% CI, all values within its range are equally likely, i.e., values in the centre of the confidence interval are equally like as those located at the outer extremes. Furthermore, the range of 95% CI does not entail 95% of the most credible parameter values. The choses terminology is in actuality very misleading as it gives the impression that the 95% CI carries information about the confidentiality of the values it entails (which it does not) The related widely shared logical fallacies are discussed in chapter xxx. The Bayesian HDI does what the CI pretends to do. For example, a 95% HDI is based on a density distribution, meaning that values in its centre are more likely than those at the margin, viz., the total probability of parameter values within the HDI is 95%. The HDI encompasses a large number of parameter values that are jointly credible, given the empirical data. In other terms, the HDI provides distributions of credible values of θ, not merely point estimates as is the case with CIs. Thus, the HDI can be considered as a measure of precision of the Bayesian parameter estimation it provides a summary of the distribution of the credible values of θ. Another major advantage of HDIs over Cis is their insensitivity with regards to sampling strategies and other data-collection idiosyncrasies that distort (and oftentimes logically invalidate) the interpretation of *p*-values, and therefore Cis (which are based on p values). The statistical inadequacies of CIs (which are nowadays advertised as an integral part of "the new statistics") are discussed in greater detail in chapter xxx.

The specified HDI can also be utilised in order to decide which values for θ are credible (given the empirical data). For this purpose, a "*Region of Practical Interest*" (ROPE)[243] is constructed around the value of θ. Consider a ROPE for $\theta = 0$ (i.e., $\mu_1 - \mu_2 = 0$) is defined. The 95% ROPE defines a narrow interval which specifies values that are

[243] The literature contains a multifarious nomenclature to refer to "regions of practical equivalence". Synonymous terms are, inter alia: "smallest effect size of interest", "range of equivalence," "interval of clinical equivalence," and "indifference zone," etcetera (but see Kruschke & Liddell, 2017b).

deemed equivalent to $\theta = 0$. That is, *for all practical purpose*, values that lie within the Region of Practical Interest are regarded as equivalent to $\theta = 0$. The ROPE procedure allows flexibility in decision-making which is not available in other conventional procedures (e.g., NHST). Another significant advantage is that no correction for multiple comparisons are needed because no *p* values are involved. In other words, the analysis does not have to take α- inflation into account (Kruschke & Vanpaemel, 2015). However, it should be emphasized that the Bayesian procedure is not immune to α-errors (false alarms). The Bayesian analysis (and any other class of analyses) can lead to fallacious conclusions if the data is not representative of the population of interest (due to sampling bias, response bias, or any number of other potentially confounding factors).

The crucial analytic question is: Are any of the values within the ROPE *sufficiently credible* given the empirical data at hand? This question can be solved by consulting the HDI. We asserted in the previous paragraphs that any value that falls within the High Density Interval can be declared as reasonably credible/believable. It follows logically that a given ROPE value is regarded as incredible if it does not lie within the HDI and, vice versa, ROPE values that fall within the HDI are considered credible. The heuristic "accept versus reject" decision rule based on the HDI and the ROPE can thus be summarized with the following two statements:

"A parameter value is declared to be not credible, or rejected, if its entire ROPE lies outside the 95% highest density interval (HDI) of the posterior distribution of that parameter."

"A parameter value is declared to be accepted for practical purposes if that value's ROPE completely contains the 95% HDI of the posterior of that parameter."

(Dieudonne, 1970)

Expressed as a logical representation, the decision rule can be stated as follows.

Equation 21. HDI and ROPE based decision algorithm for hypothesis testing.

$$P(\mathrm{HDI}_{0.95} \cap \mathrm{ROPE} = \emptyset \mid \mathrm{data}) \in \{0,1\}.$$

where ∈ denotes the set membership, ∩ the intersection, and ∅ is the Bourbaki notation (Festa, 1993, p. 22, content in braket added) denoting an empty set containing no elements.

A related question is: What is the probability that θ is enclosed by the ROPE (has set membership). This question can be posed as follows:

$$P(\theta \in \mathrm{ROPE} \mid \mathrm{data}).$$

The ROPE is specified by taking theoretical considerations and a prior knowledge into account. The researcher must determine what "practically equivalent" means in the specific experimental context at hand, that is, which values around the landmark of zero are to be regarded as equal to zero. This decision should ideally be made a priori and independent from the empirical data observed in the current experimental situation. Hence, the ROPE is predetermined fixed interval (i.e., a constant with no variance). The 95% HDI on the other hand, is entirely defined by the postulated model and the empirical data.

As opposed to NHST, the ROPE based decision procedure can both reject and accept the null (can only reject). The question becomes: Should be accept the null value as indicated by the HDI/ROPE procedure? Given that the limits of the ROPE are subjectively determined one would like to know what the conclusion would be if we had specified a ROPE with different bounds. The posterior distribution in combination with the parameters of the 95% HDI is *de facto* all that is needed to evaluate if a different (e.g., narrower) ROPE would still lead to the conclusion to accept the null value.

In sum, it can be concluded that the discrete (binary) decision about the credibility of parameter values based on the combination of HDI and ROPE indicates that there is no difference for the means between experimental condition v00 versus v01. More specifically, because the 95% HDI was contained within the ROPE we concluded that the difference between means is practically equivalent to zero. It should be underscored that this is a pragmatic decision based on Bayesian (propositional) logic and not a frequentists interpretation. Moreover, it should be emphasized that the reduction of an information rich posterior probability distribution into a binary "yes versus no" decision is based on several additional assumptions that are independent of the informational value of the HDI. The HDI conveys valuable distribution information about the parameter in question, independent from its auxiliary role in deciding about a point-hypothesis (i.e., whether $\mu_1 - \mu_2 = 0$).
Reporting the exact 95% HDI allows the sceptical reader to construct their own subjectively/empirically motivated ROPE for comparison.

Appendix B23 Bayesian parameter estimation via Markov Chain Monte Carlo methods

The “BEST” model (Kruschke, 2015) for Bayesian parameter estimation using Markov Chain Monte Carlo simulations (Experiment 1)

```
#download data from webserver and import as table
 dataexp1 <-
  read.table("http://www.irrational-decisions.com/phd-thesis/dataexp1.csv",
             header=TRUE, sep=",", na.strings="NA", dec=".",
strip.white=TRUE)


  #BEST function (Kruschke, 2013, 2014)
  BESTmcmc = function( y1, y2, numSavedSteps=100000, thinSteps=1,
showMCMC=FALSE) {
  # This function generates an MCMC sample from the posterior distribution.
  # Description of arguments:
  # showMCMC is a flag for displaying diagnostic graphs of the chains.
  #     If F (the default), no chain graphs are displayed. If T, they are.
  # Description of arguments:
  # showMCMC is a flag for displaying diagnostic graphs of the chains.
  #     If F (the default), no chain graphs are displayed. If T, they are.
  require(rjags)
  #(Plummer, 2016)
  #------------------------------------------------------------------------
------
  # THE MODEL.
  modelString = "
  model {
    for ( i in 1:Ntotal ) {
```

```
    y[i] ~ dt( mu[x[i]] , tau[x[i]] , nu )
  }
  for ( j in 1:2 ) {
    mu[j] ~ dnorm( muM , muP )
    tau[j] <- 1/pow( sigma[j] , 2 )
    sigma[j] ~ dunif( sigmaLow , sigmaHigh )
  }
  nu <- nuMinusOne+1
  nuMinusOne ~ dexp(1/29)
}
" # close quote for modelString
# Write out modelString to a text file
writeLines( modelString , con="BESTmodel.txt" )

#-----------------------------------------------------------------------
------
# THE DATA.
# Load the data:
y = c( y1 , y2 ) # combine data into one vector
x = c( rep(1,length(y1)) , rep(2,length(y2)) ) # create group membership
code
Ntotal = length(y)
# Specify the data in a list, for later shipment to JAGS:
dataList = list(
  y = y ,
  x = x ,
  Ntotal = Ntotal ,
  muM = mean(y) ,
  muP = 0.000001 * 1/sd(y)^2 ,
```

```
    sigmaLow = sd(y) / 1000 ,
    sigmaHigh = sd(y) * 1000
  )

  #-----------------------------------------------------------------------
------
  # INTIALIZE THE CHAINS.
  # Initial values of MCMC chains based on data:
  mu = c( mean(y1) , mean(y2) )
  sigma = c( sd(y1) , sd(y2) )
  # Regarding initial values in next line: (1) sigma will tend to be too
big if
  # the data have outliers, and (2) nu starts at 5 as a moderate value.
These
  # initial values keep the burn-in period moderate.
  initsList = list( mu = mu , sigma = sigma , nuMinusOne = 4 )

  #-----------------------------------------------------------------------
------
  # RUN THE CHAINS

  parameters = c( "mu" , "sigma" , "nu" )     # The parameters to be
monitored
  adaptSteps = 500              # Number of steps to "tune" the samplers
  burnInSteps = 1000
  nChains = 3
  nIter = ceiling( ( numSavedSteps * thinSteps ) / nChains )
  # Create, initialize, and adapt the model:
```

```
  jagsModel = jags.model( "BESTmodel.txt" , data=dataList , inits=initsList
,
                          n.chains=nChains , n.adapt=adaptSteps )
  # Burn-in:
  cat( "Burning in the MCMC chain...\n" )
  update( jagsModel , n.iter=burnInSteps )
  # The saved MCMC chain:
  cat( "Sampling final MCMC chain...\n" )
  codaSamples = coda.samples( jagsModel , variable.names=parameters ,
                              n.iter=nIter , thin=thinSteps )
  # resulting codaSamples object has these indices:
  #   codaSamples[[ chainIdx ]][ stepIdx , paramIdx ]

  #Coda package (Martyn et al., 2016)

    # EXAMINE THE RESULTS
  if ( showMCMC ) {
    openGraph(width=7,height=7)
    autocorr.plot( codaSamples[[1]] , ask=FALSE )
    show( gelman.diag( codaSamples ) )
    effectiveChainLength = effectiveSize( codaSamples )
    show( effectiveChainLength )
  }

  # Convert coda-object codaSamples to matrix object for easier handling.
  # But note that this concatenates the different chains into one long
chain.
  # Result is mcmcChain[ stepIdx , paramIdx ]
  mcmcChain = as.matrix( codaSamples )
```

```
  return( mcmcChain )

} # end function BESTmcmc

#==========================================================================
====

BESTsummary = function( y1 , y2 , mcmcChain ) {
  source("HDIofMCMC.R")
  mcmcSummary = function( paramSampleVec , compVal=NULL ) {
    meanParam = mean( paramSampleVec )
    medianParam = median( paramSampleVec )
    dres = density( paramSampleVec )
    modeParam = dres$x[which.max(dres$y)]
    hdiLim = HDIofMCMC( paramSampleVec )
    if ( !is.null(compVal) ) {
      pcgtCompVal = ( 100 * sum( paramSampleVec > compVal )
                      / length( paramSampleVec ) )
    } else {
      pcgtCompVal=NA
    }
    return( c( meanParam , medianParam , modeParam , hdiLim , pcgtCompVal )
)
  }
  # Define matrix for storing summary info:
  summaryInfo = matrix( 0 , nrow=9 , ncol=6 , dimnames=list(
    PARAMETER=c( "mu1" , "mu2" , "muDiff" , "sigma1" , "sigma2" ,
"sigmaDiff" ,
             "nu" , "nuLog10" , "effSz" ),
```

```
    SUMMARY.INFO=c( "mean" , "median" , "mode" , "HDIlow" , "HDIhigh" ,
                    "pcgtZero" )
    ) )
  summaryInfo[ "mu1" , ] = mcmcSummary( mcmcChain[,"mu[1]"] )
  summaryInfo[ "mu2" , ] = mcmcSummary( mcmcChain[,"mu[2]"] )
  summaryInfo[ "muDiff" , ] = mcmcSummary( mcmcChain[,"mu[1]"]
                                          - mcmcChain[,"mu[2]"] ,
                                          compVal=0 )
  summaryInfo[ "sigma1" , ] = mcmcSummary( mcmcChain[,"sigma[1]"] )
  summaryInfo[ "sigma2" , ] = mcmcSummary( mcmcChain[,"sigma[2]"] )
  summaryInfo[ "sigmaDiff" , ] = mcmcSummary( mcmcChain[,"sigma[1]"]
                                             - mcmcChain[,"sigma[2]"] ,
                                             compVal=0 )
  summaryInfo[ "nu" , ] = mcmcSummary( mcmcChain[,"nu"] )
  summaryInfo[ "nuLog10" , ] = mcmcSummary( log10(mcmcChain[,"nu"]) )

  N1 = length(y1)
  N2 = length(y2)
  effSzChain = ( ( mcmcChain[,"mu[1]"] - mcmcChain[,"mu[2]"] )
            / sqrt( ( mcmcChain[,"sigma[1]"]^2 + mcmcChain[,"sigma[2]"]^2 )
/ 2 ) )
  summaryInfo[ "effSz" , ] = mcmcSummary( effSzChain , compVal=0 )
  # Or, use sample-size weighted version:
  # effSz = ( mu1 - mu2 ) / sqrt( ( sigma1^2 *(N1-1) + sigma2^2 *(N2-1) )
  #                               / (N1+N2-2) )
  # Be sure also to change plot label in BESTplot function, below.
  return( summaryInfo )
}
```

```
#==========================================================================
====

BESTplot = function( y1 , y2 , mcmcChain , ROPEm=NULL , ROPEsd=NULL ,
                    ROPEeff=NULL , showCurve=FALSE , pairsPlot=FALSE ) {
  # This function plots the posterior distribution (and data).
  # Description of arguments:
  # y1 and y2 are the data vectors.
  # mcmcChain is a list of the type returned by function BTT.
  # ROPEm is a two element vector, such as c(-1,1), specifying the limit
  #    of the ROPE on the difference of means.
  # ROPEsd is a two element vector, such as c(-1,1), specifying the limit
  #    of the ROPE on the difference of standard deviations.
  # ROPEeff is a two element vector, such as c(-1,1), specifying the limit
  #    of the ROPE on the effect size.
  # showCurve is TRUE or FALSE and indicates whether the posterior should
  #    be displayed as a histogram (by default) or by an approximate curve.
  # pairsPlot is TRUE or FALSE and indicates whether scatterplots of pairs
  #    of parameters should be displayed.
  mu1 = mcmcChain[,"mu[1]"]
  mu2 = mcmcChain[,"mu[2]"]
  sigma1 = mcmcChain[,"sigma[1]"]
  sigma2 = mcmcChain[,"sigma[2]"]
  nu = mcmcChain[,"nu"]
  if ( pairsPlot ) {
    # Plot the parameters pairwise, to see correlations:
    openGraph(width=7,height=7)
    nPtToPlot = 1000
    plotIdx = floor(seq(1,length(mu1),by=length(mu1)/nPtToPlot))
```

```
  panel.cor = function(x, y, digits=2, prefix="", cex.cor, ...) {
    usr = par("usr"); on.exit(par(usr))
    par(usr = c(0, 1, 0, 1))
    r = (cor(x, y))
    txt = format(c(r, 0.123456789), digits=digits)[1]
    txt = paste(prefix, txt, sep="")
    if(missing(cex.cor)) cex.cor <- 0.8/strwidth(txt)
    text(0.5, 0.5, txt, cex=1.25 ) # was cex=cex.cor*r
  }
  pairs( cbind( mu1 , mu2 , sigma1 , sigma2 , log10(nu) )[plotIdx,] ,
         labels=c( expression(mu[1]) , expression(mu[2]) ,
                   expression(sigma[1]) , expression(sigma[2]) ,
                   expression(log10(nu)) ) ,
         lower.panel=panel.cor , col="skyblue" )
}
source("plotPost.R")
# Set up window and layout:
openGraph(width=6.0,height=8.0)
layout( matrix( c(4,5,7,8,3,1,2,6,9,10) , nrow=5, byrow=FALSE ) )
par( mar=c(3.5,3.5,2.5,0.5) , mgp=c(2.25,0.7,0) )

# Select thinned steps in chain for plotting of posterior predictive
curves:
chainLength = NROW( mcmcChain )
nCurvesToPlot = 30
stepIdxVec = seq( 1 , chainLength , floor(chainLength/nCurvesToPlot) )
xRange = range( c(y1,y2) )
xLim = c( xRange[1]-0.1*(xRange[2]-xRange[1]) ,
          xRange[2]+0.1*(xRange[2]-xRange[1]) )
```

```
  xVec = seq( xLim[1] , xLim[2] , length=200 )
  maxY = max( dt( 0 , df=max(nu[stepIdxVec]) ) /
    min(c(sigma1[stepIdxVec],sigma2[stepIdxVec])) )
  # Plot data y1 and smattering of posterior predictive curves:
  stepIdx = 1
  plot( xVec , dt( (xVec-
mu1[stepIdxVec[stepIdx]])/sigma1[stepIdxVec[stepIdx]] ,
                   df=nu[stepIdxVec[stepIdx]] )/sigma1[stepIdxVec[stepIdx]]
,
        ylim=c(0,maxY) , cex.lab=1.75 ,
        type="l" , col="skyblue" , lwd=1 , xlab="y" , ylab="p(y)" ,
        main="Data Group 1 w. Post. Pred." )
  for ( stepIdx in 2:length(stepIdxVec) ) {
    lines(xVec, dt( (xVec-
mu1[stepIdxVec[stepIdx]])/sigma1[stepIdxVec[stepIdx]] ,
                      df=nu[stepIdxVec[stepIdx]]
)/sigma1[stepIdxVec[stepIdx]] ,
           type="l" , col="skyblue" , lwd=1 )
  }
  histBinWd = median(sigma1)/2
  histCenter = mean(mu1)
  histBreaks = sort( c( seq( histCenter-histBinWd/2 , min(xVec)-histBinWd/2
,
                             -histBinWd ),
                        seq( histCenter+histBinWd/2 , max(xVec)+histBinWd/2
,
                             histBinWd ) , xLim ) )
  histInfo = hist( y1 , plot=FALSE , breaks=histBreaks )
  yPlotVec = histInfo$density
```

```
  yPlotVec[ yPlotVec==0.0 ] = NA

  xPlotVec = histInfo$mids

  xPlotVec[ yPlotVec==0.0 ] = NA

  points( xPlotVec , yPlotVec , type="h" , lwd=3 , col="red" )

  text( max(xVec) , maxY , bquote(N[1]==.(length(y1))) , adj=c(1.1,1.1) )

  # Plot data y2 and smattering of posterior predictive curves:

  stepIdx = 1

  plot( xVec , dt( (xVec-
mu2[stepIdxVec[stepIdx]])/sigma2[stepIdxVec[stepIdx]] ,

                   df=nu[stepIdxVec[stepIdx]] )/sigma2[stepIdxVec[stepIdx]]
,

        ylim=c(0,maxY) , cex.lab=1.75 ,

        type="l" , col="skyblue" , lwd=1 , xlab="y" , ylab="p(y)" ,

        main="Data Group 2 w. Post. Pred." )

  for ( stepIdx in 2:length(stepIdxVec) ) {

    lines(xVec, dt( (xVec-
mu2[stepIdxVec[stepIdx]])/sigma2[stepIdxVec[stepIdx]] ,

                      df=nu[stepIdxVec[stepIdx]]
)/sigma2[stepIdxVec[stepIdx]] ,

           type="l" , col="skyblue" , lwd=1 )

  }

  histBinWd = median(sigma2)/2

  histCenter = mean(mu2)

  histBreaks = sort( c( seq( histCenter-histBinWd/2 , min(xVec)-histBinWd/2
,

                             -histBinWd ),

                        seq( histCenter+histBinWd/2 , max(xVec)+histBinWd/2
,

                             histBinWd ) , xLim ) )
```

```
  histInfo = hist( y2 , plot=FALSE , breaks=histBreaks )
  yPlotVec = histInfo$density
  yPlotVec[ yPlotVec==0.0 ] = NA
  xPlotVec = histInfo$mids
  xPlotVec[ yPlotVec==0.0 ] = NA
  points( xPlotVec , yPlotVec , type="h" , lwd=3 , col="red" )
  text( max(xVec) , maxY , bquote(N[2]==.(length(y2))) , adj=c(1.1,1.1) )

  # Plot posterior distribution of parameter nu:
  histInfo = plotPost( log10(nu) , col="skyblue" , # breaks=30 ,
                      showCurve=showCurve ,
                 xlab=bquote("log10("*nu*")") , cex.lab = 1.75 ,
showMode=TRUE ,
                 main="Normality" ) #  (<0.7 suggests kurtosis)

  # Plot posterior distribution of parameters mu1, mu2, and their
difference:
  xlim = range( c( mu1 , mu2 ) )
  histInfo = plotPost( mu1 ,  xlim=xlim , cex.lab = 1.75 ,
                      showCurve=showCurve ,
                 xlab=bquote(mu[1]) , main=paste("Group",1,"Mean") ,
                 col="skyblue" )
  histInfo = plotPost( mu2 ,  xlim=xlim , cex.lab = 1.75 ,
                      showCurve=showCurve ,
                 xlab=bquote(mu[2]) , main=paste("Group",2,"Mean") ,
                 col="skyblue" )
  histInfo = plotPost( mu1-mu2 , compVal=0 ,  showCurve=showCurve ,
                 xlab=bquote(mu[1] - mu[2]) , cex.lab = 1.75 , ROPE=ROPEm
,
```

```
                  main="Difference of Means" , col="skyblue" )

  # Plot posterior distribution of param's sigma1, sigma2, and their
difference:
  xlim=range( c( sigma1 , sigma2 ) )
  histInfo = plotPost( sigma1 ,  xlim=xlim , cex.lab = 1.75 ,
                       showCurve=showCurve ,
                  xlab=bquote(sigma[1]) , main=paste("Group",1,"Std. Dev.")
,
                  col="skyblue" , showMode=TRUE )
  histInfo = plotPost( sigma2 ,  xlim=xlim , cex.lab = 1.75 ,
                       showCurve=showCurve ,
                  xlab=bquote(sigma[2]) , main=paste("Group",2,"Std. Dev.")
,
                  col="skyblue" , showMode=TRUE )
  histInfo = plotPost( sigma1-sigma2 ,
                       compVal=0 ,  showCurve=showCurve ,
                       xlab=bquote(sigma[1] - sigma[2]) , cex.lab = 1.75 ,
                       ROPE=ROPEsd ,
               main="Difference of Std. Dev.s" , col="skyblue" ,
showMode=TRUE )

  # Plot of estimated effect size. Effect size is d-sub-a from
  # Macmillan & Creelman, 1991; Simpson & Fitter, 1973; Swets, 1986a,
1986b.

  effectSize = ( mu1 - mu2 ) / sqrt( ( sigma1^2 + sigma2^2 ) / 2 )
  histInfo = plotPost( effectSize , compVal=0 ,  ROPE=ROPEeff ,
                        showCurve=showCurve ,
```

```
                  xlab=bquote( (mu[1]-mu[2])
                    /sqrt((sigma[1]^2 +sigma[2]^2 )/2 ) ),
            showMode=TRUE , cex.lab=1.0 , main="Effect Size" ,
col="skyblue" )
  # Or use sample-size weighted version:
  # Hedges 1981; Wetzels, Raaijmakers, Jakab & Wagenmakers 2009.
  # N1 = length(y1)
  # N2 = length(y2)
  # effectSize = ( mu1 - mu2 ) / sqrt( ( sigma1^2 *(N1-1) + sigma2^2 *(N2-
1) )
  #                                    / (N1+N2-2) )
  # Be sure also to change BESTsummary function, above.
  # histInfo = plotPost( effectSize , compVal=0 ,  ROPE=ROPEeff ,
  #           showCurve=showCurve ,
  #           xlab=bquote( (mu[1]-mu[2])
  #           /sqrt((sigma[1]^2 *(N[1]-1)+sigma[2]^2 *(N[2]-1))/(N[1]+N[2]-
2)) ),
  #           showMode=TRUE , cex.lab=1.0 , main="Effect Size" ,
col="skyblue" )
  return( BESTsummary( y1 , y2 , mcmcChain ) )
} # end of function BESTplot
```

Appendix B24 Markov Chain convergence diagnostics for condition V_{00} and V_{10}

This appendix contains the MCMC convergence diagnostic (i.e., ESS and MCSE) for all parameters. The graphics show the trace plot, autocorrelation plot, shrink factor plot, and the density plot. All indices indicate that the stationary (equilibrium) distribution π has been reached.

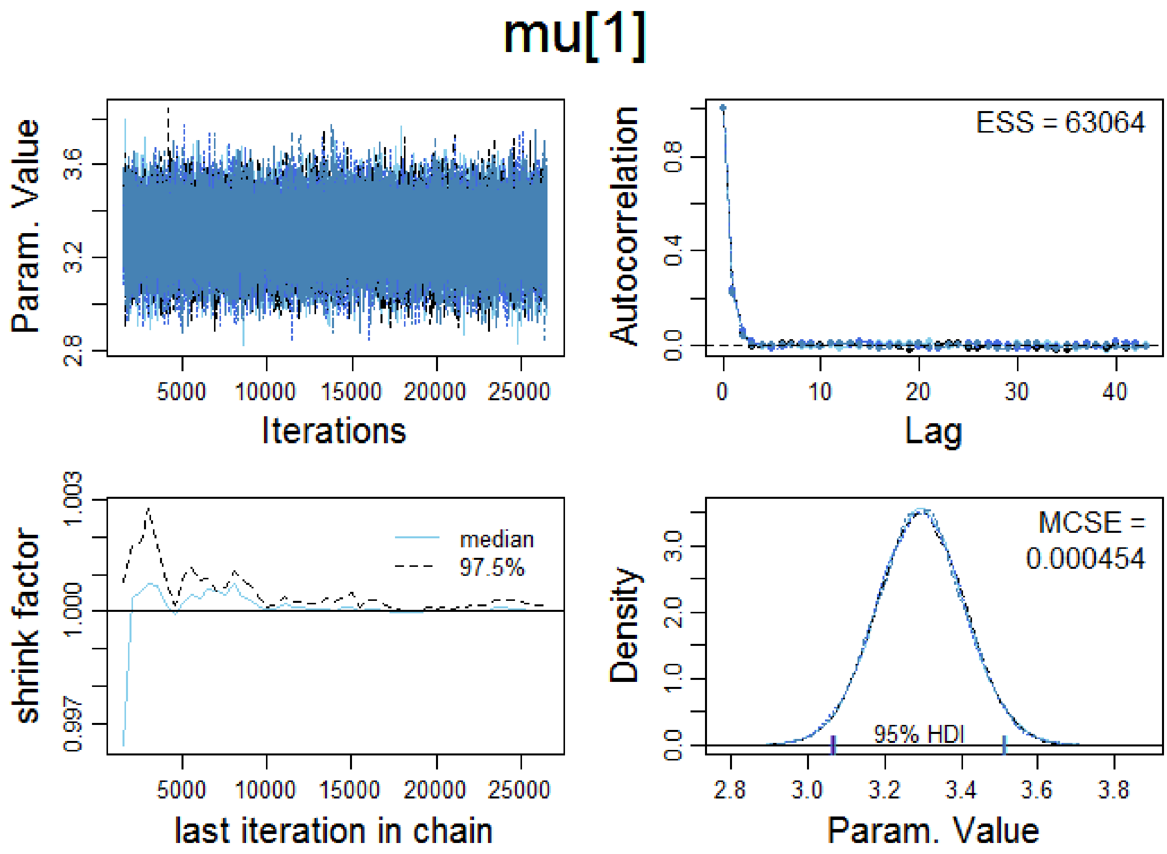


Figure 113. MCMC diagnostics for μ_1 (experimental condition V_{00}).

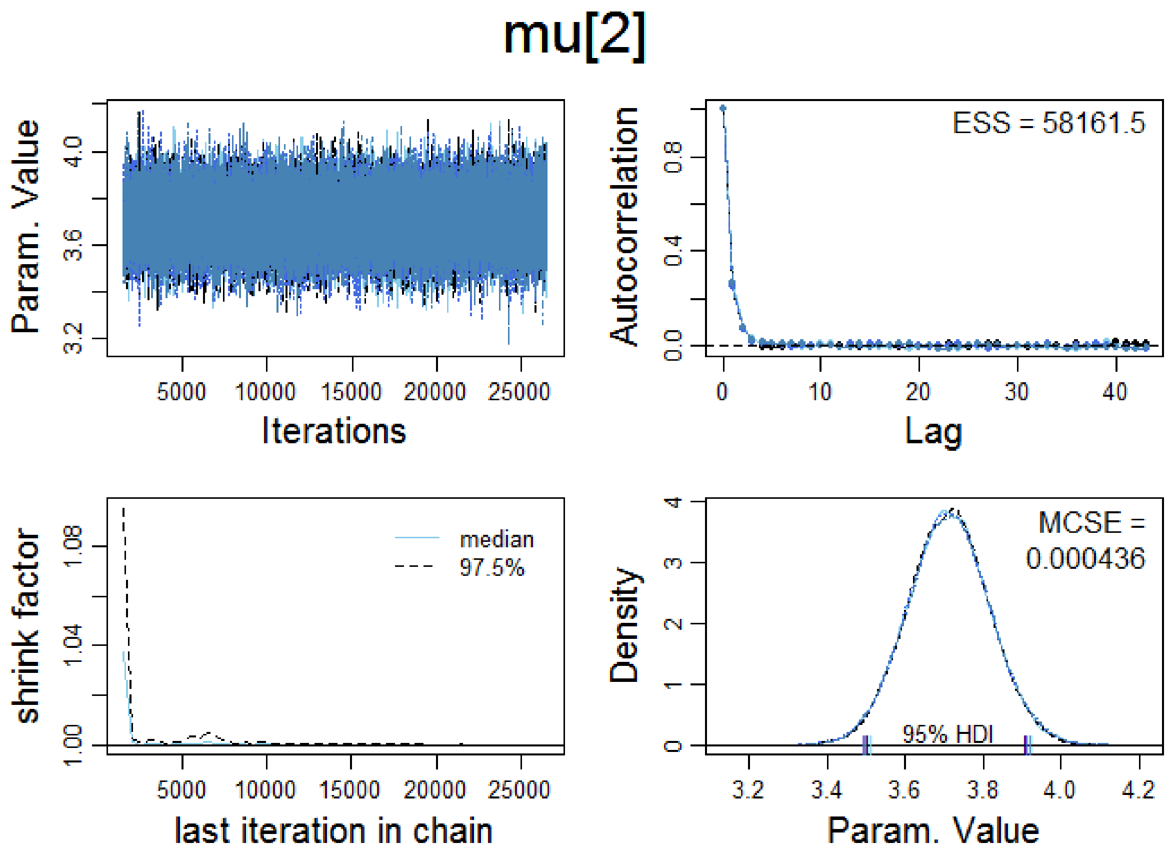


Figure 114. MCMC diagnostics for μ_2 (experimental condition V_{01}).

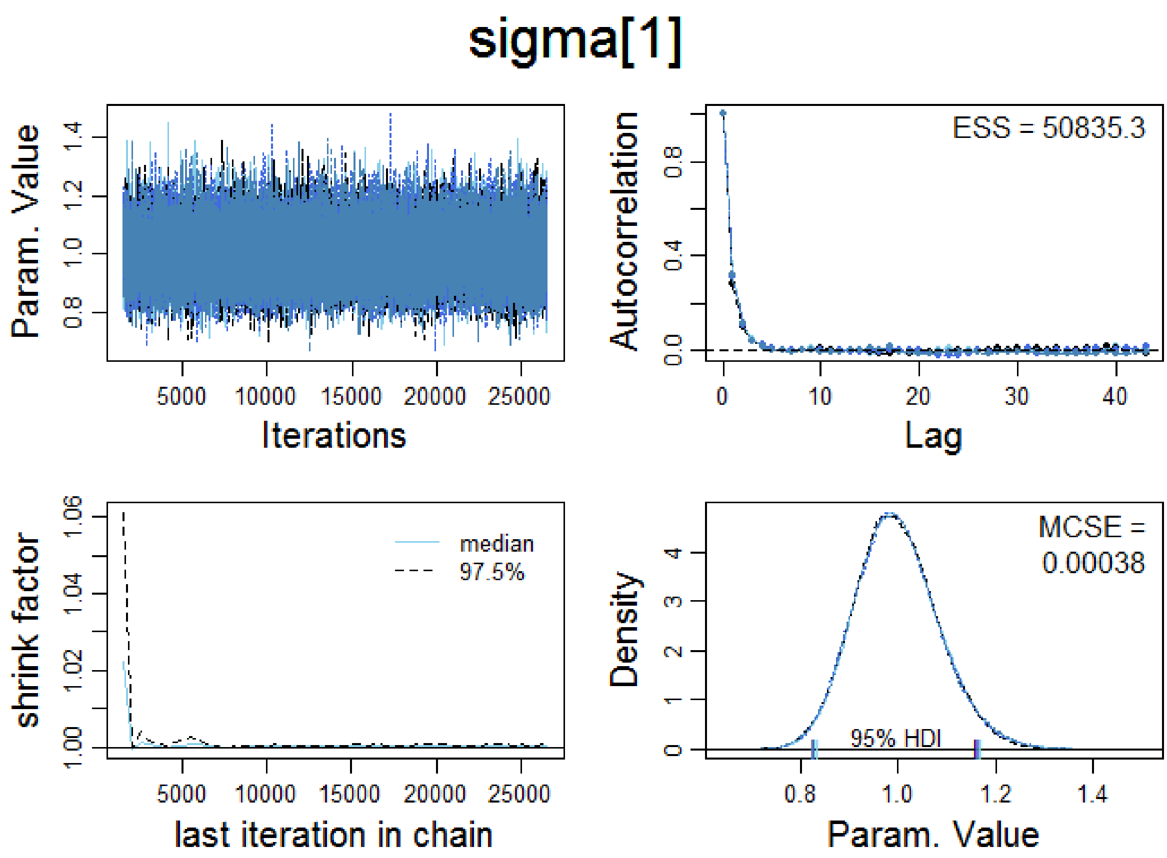


Figure 115. MCMC diagnostics for σ_1 (experimental condition V_{00}).

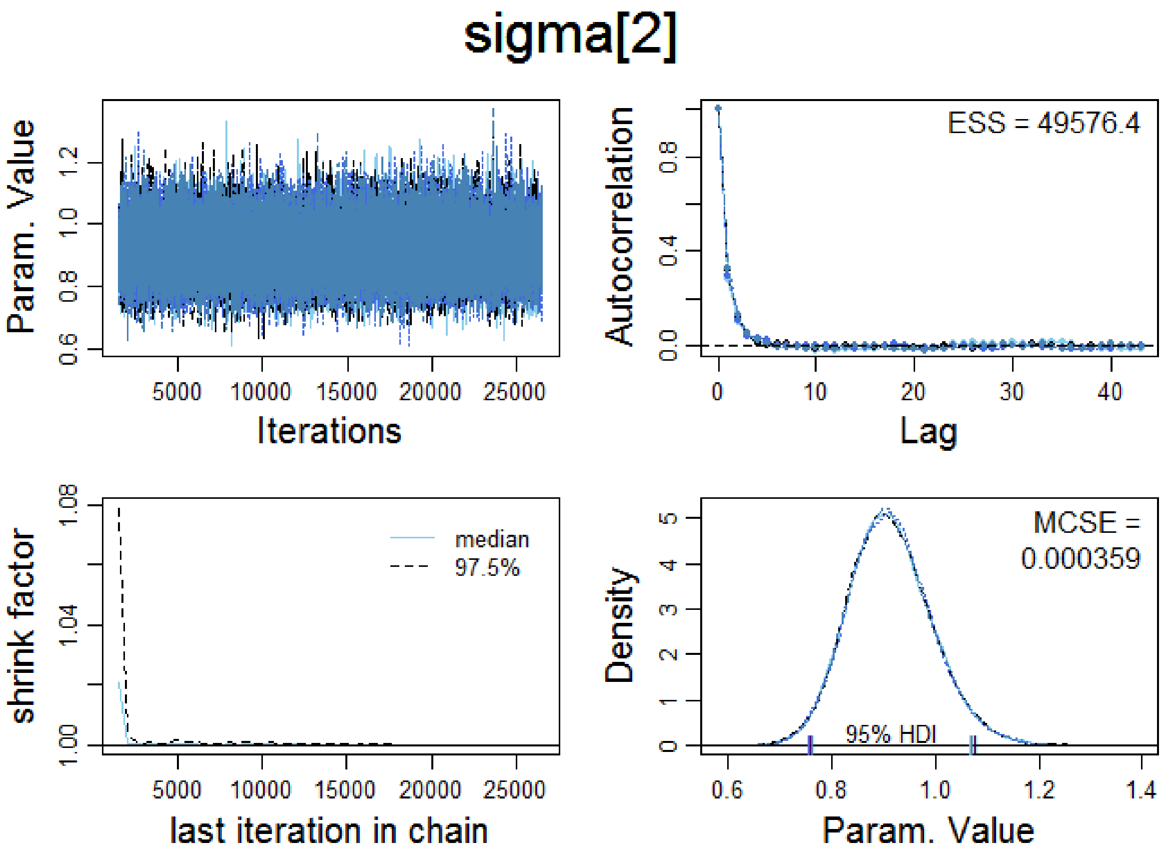


Figure 116. MCMC diagnostics for σ_2 (experimental condition V_{11}).

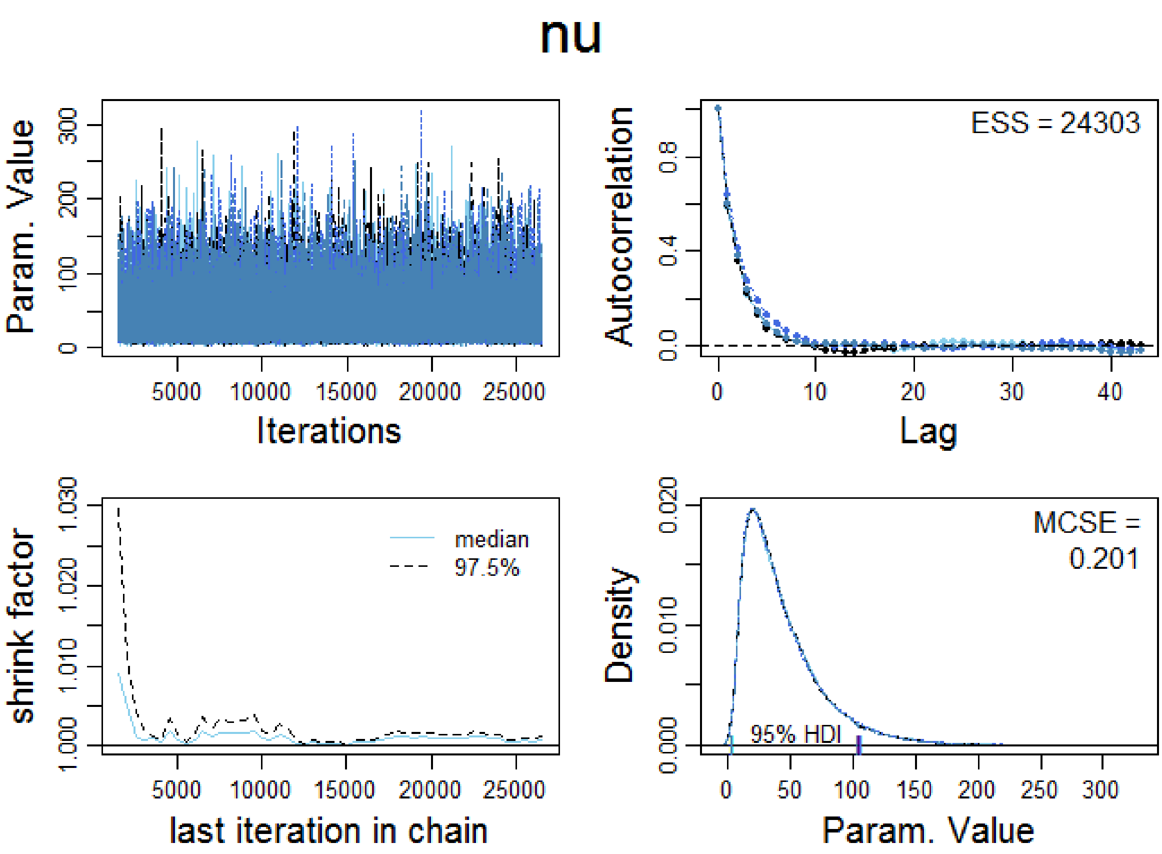


Figure 117. MCMC diagnostics for *v*.

Appendix B25 Markov Chain convergence diagnostics for condition V_{00} and V_{10} (correlational analysis)

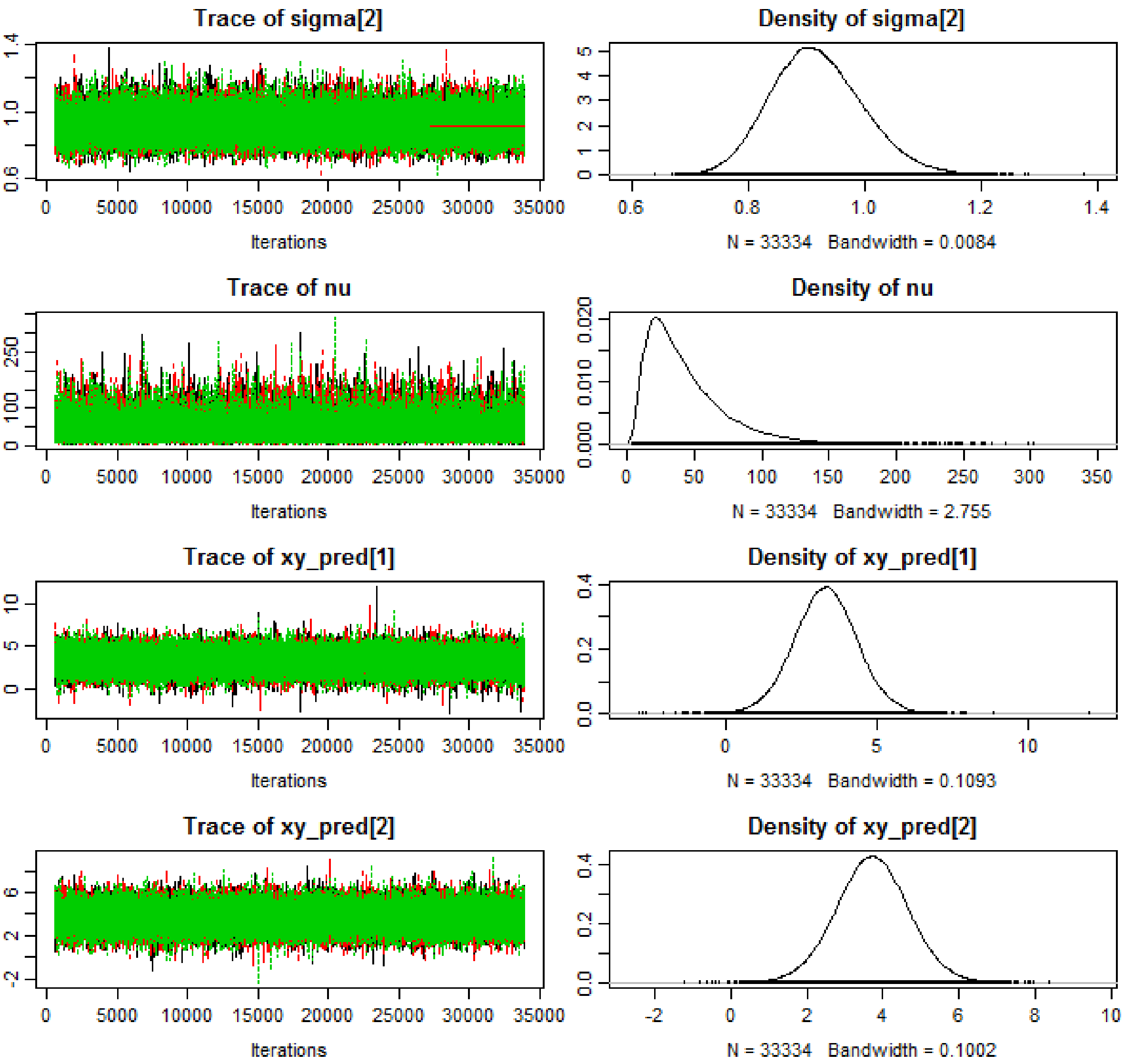
```
#download data from webserver and import as table
dataexp1 <-
  read.table("http://www.irrational-decisions.com/phd-thesis/dataexp1.csv",
             header=TRUE, sep=",", na.strings="NA", dec=".",
strip.white=TRUE)

# Model code for the Bayesian alternative to Pearson's correlation test.
# (Bååth, 2014)
require(rjags)
#(Plummer, 2016)

# Setting up the data
x <- dataexp1$v00
y <- dataexp1$v10
xy <- cbind(x, y)

# The model string written in the JAGS language
model_string <- "model {
  for(i in 1:n) {
    xy[i,1:2] ~ dmt(mu[], prec[ , ], nu)
  }

  xy_pred[1:2] ~ dmt(mu[], prec[ , ], nu)

  # JAGS parameterizes the multivariate t using precision (inverse of
variance)
  # rather than variance, therefore here inverting the covariance matrix.
```

```
  prec[1:2,1:2] <- inverse(cov[,])

  # Constructing the covariance matrix
  cov[1,1] <- sigma[1] * sigma[1]
  cov[1,2] <- sigma[1] * sigma[2] * rho
  cov[2,1] <- sigma[1] * sigma[2] * rho
  cov[2,2] <- sigma[2] * sigma[2]

  # Priors
  rho ~ dunif(-1, 1)
  sigma[1] ~ dunif(sigmaLow, sigmaHigh)
  sigma[2] ~ dunif(sigmaLow, sigmaHigh)
  mu[1] ~ dnorm(mean_mu, precision_mu)
  mu[2] ~ dnorm(mean_mu, precision_mu)
  nu <- nuMinusOne+1
  nuMinusOne ~ dexp(1/29)
}"

# Initializing the data list and setting parameters for the priors
# that in practice will result in flat priors on mu and sigma.
data_list = list(
  xy = xy,
  n = length(x),
  mean_mu = mean(c(x, y), trim=0.2) ,
  precision_mu = 1 / (max(mad(x), mad(y))^2 * 1000000),
  sigmaLow = min(mad(x), mad(y)) / 1000 ,
  sigmaHigh = max(mad(x), mad(y)) * 1000)

# Initializing parameters to sensible starting values helps the convergence
```

```r
# of the MCMC sampling. Here using robust estimates of the mean (trimmed)
# and standard deviation (MAD).
inits_list = list(mu=c(mean(x, trim=0.2), mean(y, trim=0.2)), rho=cor(x, y,
method="spearman"),
                  sigma = c(mad(x), mad(y)), nuMinusOne = 5)

# The parameters to monitor.
params <- c("rho", "mu", "sigma", "nu", "xy_pred")

# Running the model
model <- jags.model(textConnection(model_string), data = data_list,
                    inits = inits_list, n.chains = 3, n.adapt=1000)
update(model, 500) # Burning some samples to the MCMC gods....
samples <- coda.samples(model, params, n.iter=5000)

# Inspecting the posterior
plot(samples)
summary(samples)
```

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
              mean     sd mcmc_se  n_eff Rhat
rho          0.173  0.110   0.000  54356    1
mu[1]        3.296  0.114   0.000  59397    1
mu[2]        3.717  0.106   0.000  57123    1
sigma[1]     1.004  0.086   0.000  48072    1
sigma[2]     0.920  0.080   0.000  46507    1
nu          43.528 30.588   0.199  23635    1
xy_pred[1]   3.295  1.057   0.003 100001    1
xy_pred[2]   3.716  0.969   0.003 100002    1
```

```
mcmc_se: estimated standard error of the MCMC approximation of the mea
n
n_eff: a crude measure of effective MCMC sample size.
Rhat: the potential scale reduction factor (at convergence, Rhat=1).

  Model parameters
rho: the correlation between dataexp1$v00 and dataexp1$v10
mu[1]: the mean of dataexp1$v00
sigma[1]: the scale of dataexp1$v00,
a consistent estimate of SD when nu is large.
mu[2]: the mean of dataexp1$v10
sigma[2]: the scale of dataexp1$v10
nu: the degrees-of-freedom for the bivariate t distribution
xy_pred[1]: the posterior predictive distribution of dataexp1$v00
xy_pred[2]: the posterior predictive distribution of dataexp1$v10
```


Trace of sigma[2]
Iterations
Density of sigma[2]
N = 33334 Bandwidth = 0.0084
Trace of nu
Iterations
Density of nu
N = 33334 Bandwidth = 2.755
Trace of xy_pred[1]
Iterations
Density of xy_pred[1]
N = 33334 Bandwidth = 0.1093
Trace of xy_pred[2]
Iterations
Density of xy_pred[2]
N = 33334 Bandwidth = 0.1002

```
Measures
             mean     sd  HDIlo   HDIup %<comp %>comp
rho         0.173  0.110 -0.044   0.388  0.062  0.938
mu[1]       3.296  0.114  3.073   3.520  0.000  1.000
mu[2]       3.717  0.106  3.509   3.925  0.000  1.000
sigma[1]    1.004  0.086  0.842   1.178  0.000  1.000
sigma[2]    0.920  0.080  0.771   1.082  0.000  1.000
nu         43.528 30.588  5.073 104.975  0.000  1.000
xy_pred[1]  3.295  1.057  1.200   5.380  0.002  0.998
xy_pred[2]  3.716  0.969  1.755   5.592  0.000  1.000

'HDIlo' and 'HDIup' are the limits of a 95% HDI credible interval.
'%<comp' and '%>comp' are the probabilities of the respective paramete
r being
smaller or larger than 0.

  Quantiles
            q2.5%   q25% median   q75%  q97.5%
rho        -0.049  0.099  0.175  0.249   0.384
mu[1]       3.071  3.219  3.296  3.373   3.519
mu[2]       3.509  3.646  3.717  3.787   3.925
sigma[1]    0.849  0.944  1.000  1.059   1.187
sigma[2]    0.776  0.865  0.916  0.971   1.089
nu          9.031 21.705 35.325 56.535 123.410
xy_pred[1]  1.206  2.605  3.297  3.986   5.388
xy_pred[2]  1.791  3.084  3.716  4.351   5.637
```

Appendix B26 Markov Chain convergence diagnostics for condition V_{10} and V_{11} (correlational analysis)

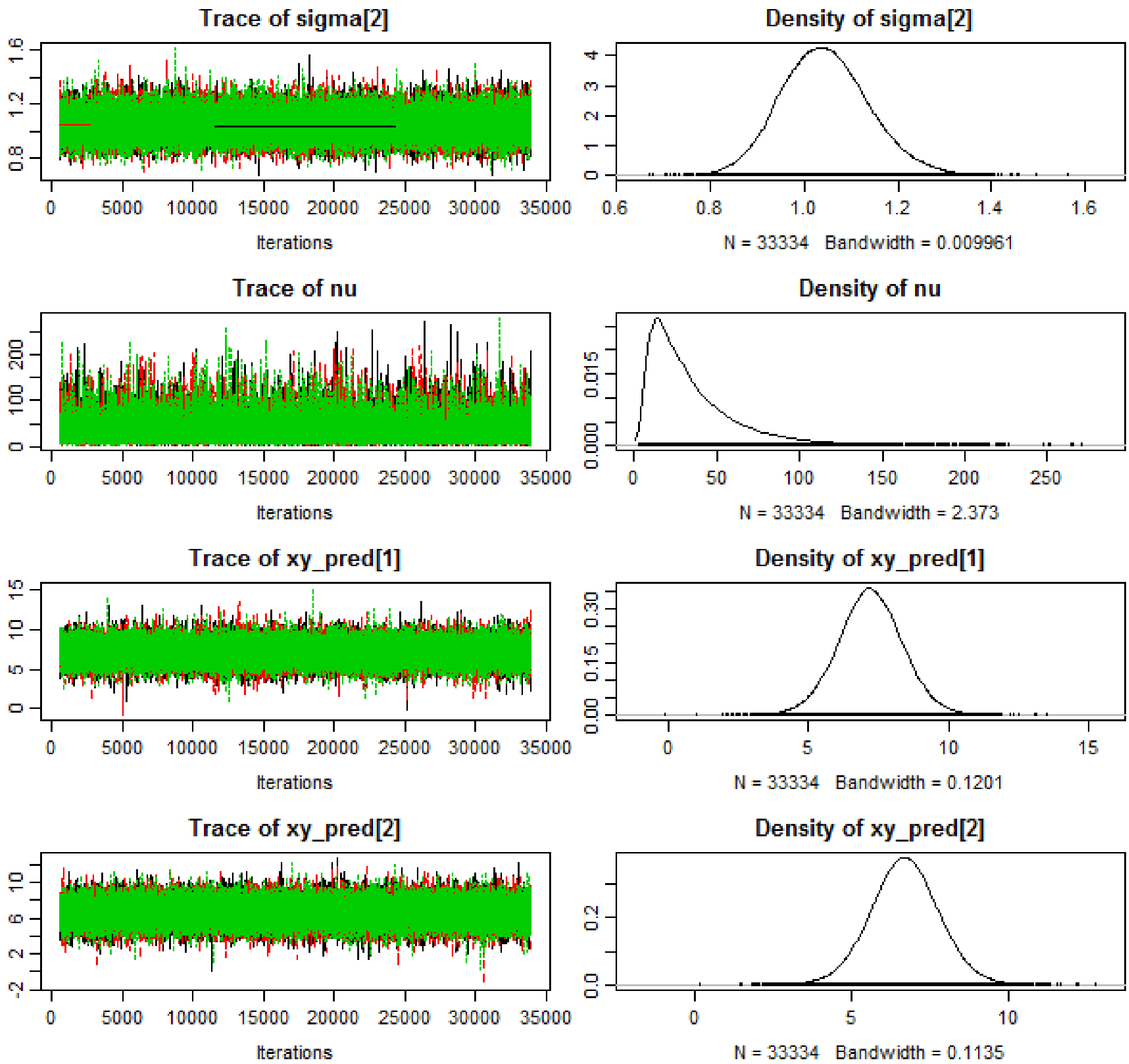
```
# Model code for the Bayesian alternative to Pearson's correlation test.
# (Bååth, 2014)
require(rjags)
#(Plummer, 2016)

#download data from webserver and import as table
dataexp1 <-
  read.table("http://www.irrational-decisions.com/phd-thesis/dataexp1.csv",
             header=TRUE, sep=",", na.strings="NA", dec=".",
strip.white=TRUE)

# Setting up the data
x <- dataexp1$v01
y <- dataexp1$v11
xy <- cbind(x, y)

# The model string written in the JAGS language
model_string <- "model {
  for(i in 1:n) {
    xy[i,1:2] ~ dmt(mu[], prec[ , ], nu)
  }

  xy_pred[1:2] ~ dmt(mu[], prec[ , ], nu)

  # JAGS parameterizes the multivariate t using precision (inverse of
variance)
  # rather than variance, therefore here inverting the covariance matrix.
```

```
  prec[1:2,1:2] <- inverse(cov[,])

  # Constructing the covariance matrix
  cov[1,1] <- sigma[1] * sigma[1]
  cov[1,2] <- sigma[1] * sigma[2] * rho
  cov[2,1] <- sigma[1] * sigma[2] * rho
  cov[2,2] <- sigma[2] * sigma[2]

  # Priors
  rho ~ dunif(-1, 1)
  sigma[1] ~ dunif(sigmaLow, sigmaHigh)
  sigma[2] ~ dunif(sigmaLow, sigmaHigh)
  mu[1] ~ dnorm(mean_mu, precision_mu)
  mu[2] ~ dnorm(mean_mu, precision_mu)
  nu <- nuMinusOne+1
  nuMinusOne ~ dexp(1/29)
}"

# Initializing the data list and setting parameters for the priors
# that in practice will result in flat priors on mu and sigma.
data_list = list(
  xy = xy,
  n = length(x),
  mean_mu = mean(c(x, y), trim=0.2) ,
  precision_mu = 1 / (max(mad(x), mad(y))^2 * 1000000),
  sigmaLow = min(mad(x), mad(y)) / 1000 ,
  sigmaHigh = max(mad(x), mad(y)) * 1000)

# Initializing parameters to sensible starting values helps the convergence
```

```
# of the MCMC sampling. Here using robust estimates of the mean (trimmed)
# and standard deviation (MAD).
inits_list = list(mu=c(mean(x, trim=0.2), mean(y, trim=0.2)), rho=cor(x, y,
method="spearman"),
                  sigma = c(mad(x), mad(y)), nuMinusOne = 5)

# The parameters to monitor.
params <- c("rho", "mu", "sigma", "nu", "xy_pred")

# Running the model
model <- jags.model(textConnection(model_string), data = data_list,
                    inits = inits_list, n.chains = 3, n.adapt=1000)
update(model, 500) # Burning some samples to the MCMC gods....
samples <- coda.samples(model, params, n.iter=5000)

# Inspecting the posterior
plot(samples)
summary(samples)
```

```
Iterations = 601:33934

Thinning interval = 1

Number of chains = 3

Sample size per chain = 33334


  Diagnostic measures

             mean     sd mcmc_se  n_eff  Rhat

rho         0.198  0.109   0.000  57872 1.000

mu[1]       7.218  0.127   0.001  54686 1.000

mu[2]       6.685  0.120   0.001  55458 1.000

sigma[1]    1.102  0.100   0.001  40148 1.000

sigma[2]    1.045  0.095   0.000  41779 1.000

nu         34.731 27.521   0.207  17853 1.001

xy_pred[1]  7.215  1.175   0.004 100001 1.000

xy_pred[2]  6.686  1.113   0.004  99369 1.000
```

```
mcmc_se: estimated standard error of the MCMC approximation of the mea
n.
n_eff: a crude measure of effective MCMC sample size.
Rhat: the potential scale reduction factor (at convergence, Rhat=1).

  Model parameters
rho: the correlation between dataexp1$v01 and dataexp1$v11
mu[1]: the mean of dataexp1$v01
sigma[1]: the scale of dataexp1$v01 , a consistent
  estimate of SD when nu is large.
mu[2]: the mean of dataexp1$v11
sigma[2]: the scale of dataexp1$v11
nu: the degrees-of-freedom for the bivariate t distribution
xy_pred[1]: the posterior predictive distribution of dataexp1$v01
xy_pred[2]: the posterior predictive distribution of dataexp1$v11
```


Trace of sigma[2]
Iterations
Density of sigma[2]
N = 33334   Bandwidth = 0.009961
Trace of nu
Iterations
Density of nu
N = 33334   Bandwidth = 2.373
Trace of xy_pred[1]
Iterations
Density of xy_pred[1]
N = 33334   Bandwidth = 0.1201
Trace of xy_pred[2]
Iterations
Density of xy_pred[2]
N = 33334   Bandwidth = 0.1135

```
Measures
              mean     sd  HDIlo  HDIup %<comp %>comp
rho          0.198  0.109 -0.017  0.409  0.038  0.962
mu[1]        7.218  0.127  6.966  7.464  0.000  1.000
mu[2]        6.685  0.120  6.447  6.921  0.000  1.000
sigma[1]     1.102  0.100  0.909  1.304  0.000  1.000
sigma[2]     1.045  0.095  0.861  1.232  0.000  1.000
nu          34.731 27.521  3.500 90.205  0.000  1.000
xy_pred[1]   7.215  1.175  4.917  9.561  0.000  1.000
xy_pred[2]   6.686  1.113  4.473  8.875  0.000  1.000

'HDIlo' and 'HDIup' are the limits of a 95% HDI credible interval.
'%<comp' and '%>comp' are the probabilities of the respective parameter being
smaller or larger than 0.

  Quantiles
             q2.5%    q25% median    q75%  q97.5%
rho         -0.021  0.124  0.200  0.273   0.405
mu[1]        6.969  7.133  7.218  7.303   7.467
mu[2]        6.448  6.605  6.685  6.765   6.922
sigma[1]     0.916  1.034  1.098  1.166   1.313
sigma[2]     0.870  0.980  1.042  1.106   1.244
nu           6.467 15.385 26.501 45.377 108.995
xy_pred[1]   4.891  6.456  7.209  7.974   9.542
xy_pred[2]   4.489  5.965  6.684  7.400   8.895
```

Appendix B27 Correlational analysis

Next, we investigate the bivariate correlations between experimental conditions. The Pearson's product-moment correlation coefficient for experimental condition V_{00} vs. V_{01} was statistically nonsignificant, $r = 0.097$, $p = 0.388$, 95% CI [-0.31, 0.12]. Ergo, this frequentist analysis indicated that H_0 cannot be rejected (i.e., the correlation is equal to zero). In addition, we computed the Bayesian equivalent of Pearson's correlation test using R and JAGS (Bååth, 2014). We defined the same noncommittal broad priors as in the previous analysis. The associated hierarchical Bayesian model is illustrated in Figure 118.

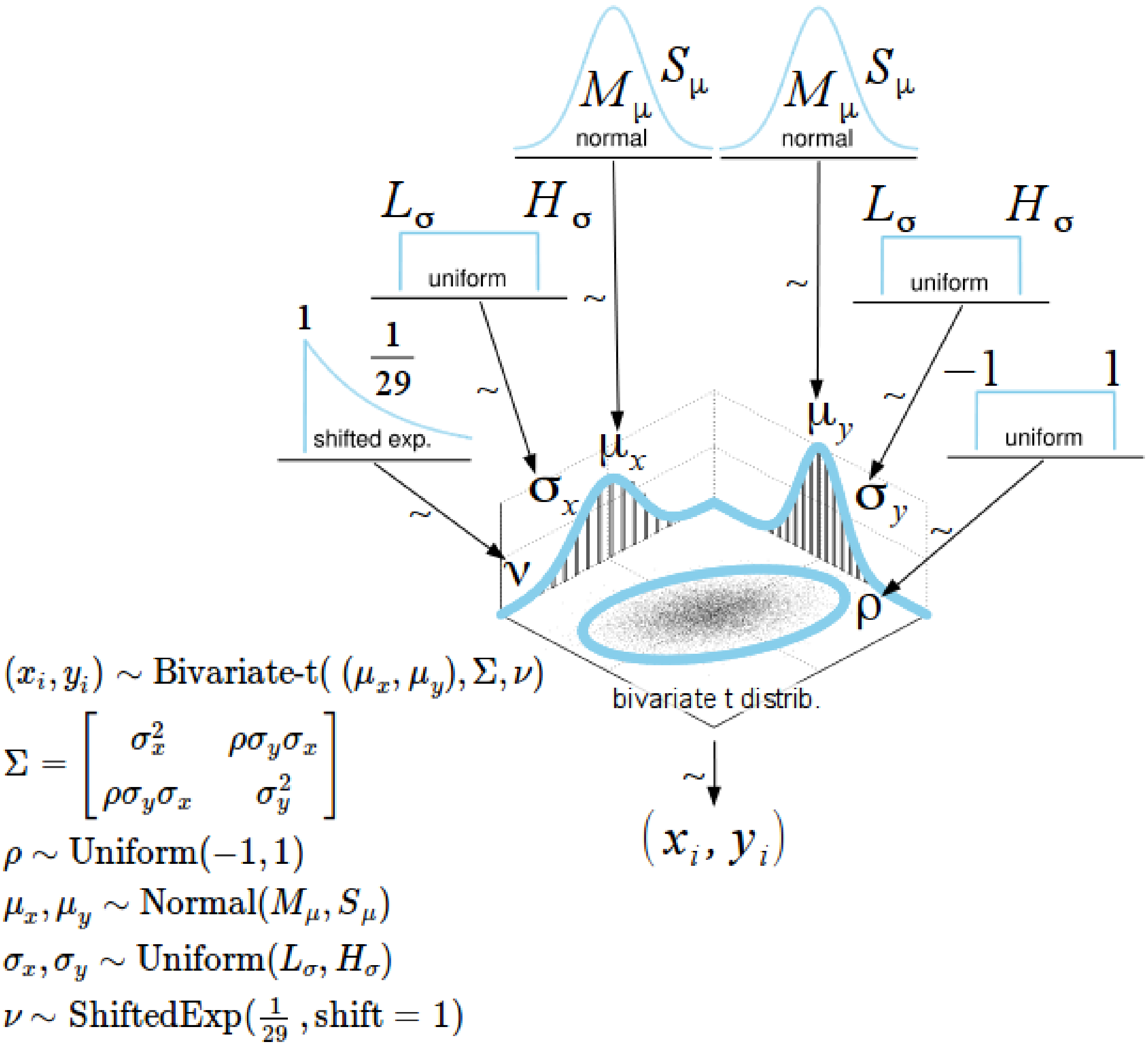


Figure 118. Pictogram of the Bayesian hierarchical model for the correlational analysis (Friendly et al., 2013). The underlying JAGS-model can be downloaded from the following URL: http://irrational-decisions.com/?page_id=2370

We performed the simulation with 1000 adaptations, 500 burn-in steps, and 10000 iterations (no thinning interval, 3 chains in parallel, sample size per chain = 33334). The convergence diagnostics indicated that the equilibrium distribution π had been reached. Various diagnostic measures are printed in

Table 51

Summary of convergence diagnostics for ρ, μ_1, μ_2, σ_1, σ_2, v, and the posterior predictive distribution of V_{00} and V_{10}.

```
Diagnostic measures
              mean     sd mcmc_se  n_eff Rhat
rho          0.173  0.110   0.000  54356    1
mu[1]        3.296  0.114   0.000  59397    1
mu[2]        3.717  0.106   0.000  57123    1
sigma[1]     1.004  0.086   0.000  48072    1
sigma[2]     0.920  0.080   0.000  46507    1
nu          43.528 30.588   0.199  23635    1
xy_pred[1]   3.295  1.057   0.003 100001    1
xy_pred[2]   3.716  0.969   0.003 100002    1
```

Model parameters:

- ρ (rho): The correlation between experimental condition V_{00} and V_{10}
- μ_1 (mu[1]): The mean of V_{00}
- σ_1 (sigma[1]): The scale of V_{00}, a consistent estimate of SD when nu is large.
- μ_2 (mu[2]): the mean of V_{10}
- σ_1 (sigma[2]): the scale of V_{10}
- v (nu): The degrees-of-freedom for the bivariate *t* distribution
- xy_pred[1]: The posterior predictive distribution of V_{00}
- xy_pred[2]: The posterior predictive distribution of V_{10}

Convergence diagnostics:

- mcmc_se: The estimated standard error of the MCMC approximation of the mean.
- n_eff: A crude measure of effective MCMC sample size.

- Rhat: the potential scale reduction factor (at convergence, Rhat=1).

The results of the Bayesian MCMC analysis indicated that the estimated correlation between condition V_{00} vs. V_{01} was $\rho = 0.17$ and the associated 95% Bayesian posterior high density credible interval ranged from [-0.05, 0.38]. Furthermore, it can be concluded that the correlation between condition V_{00} vs. V_{01} is > 0 by a probability of 0.934 (and < 0 by a probability of 0.066). The results are visualised in Figure 119. A numerical summary is given in Table 52.

Table 52

Numerical summary for all parameters associated with experimental condition V_{10} and V_{01} and their corresponding 95% posterior high density credible intervals.

Measures

	mean	sd	HDIlo	HDIup	%<comp	%>comp
rho	0.173	0.110	-0.044	0.388	0.062	0.938
mu[1]	3.296	0.114	3.073	3.520	0.000	1.000
mu[2]	3.717	0.106	3.509	3.925	0.000	1.000
sigma[1]	1.004	0.086	0.842	1.178	0.000	1.000
sigma[2]	0.920	0.080	0.771	1.082	0.000	1.000
nu	43.528	30.588	5.073	104.975	0.000	1.000
xy_pred[1]	3.295	1.057	1.200	5.380	0.002	0.998
xy_pred[2]	3.716	0.969	1.755	5.592	0.000	1.000

Note. 'HDIlo' and 'HDIup' are the limits of a 95% HDI credible interval.

'%<comp' and '%>comp' are the probabilities of the respective parameter being smaller or larger than 0.

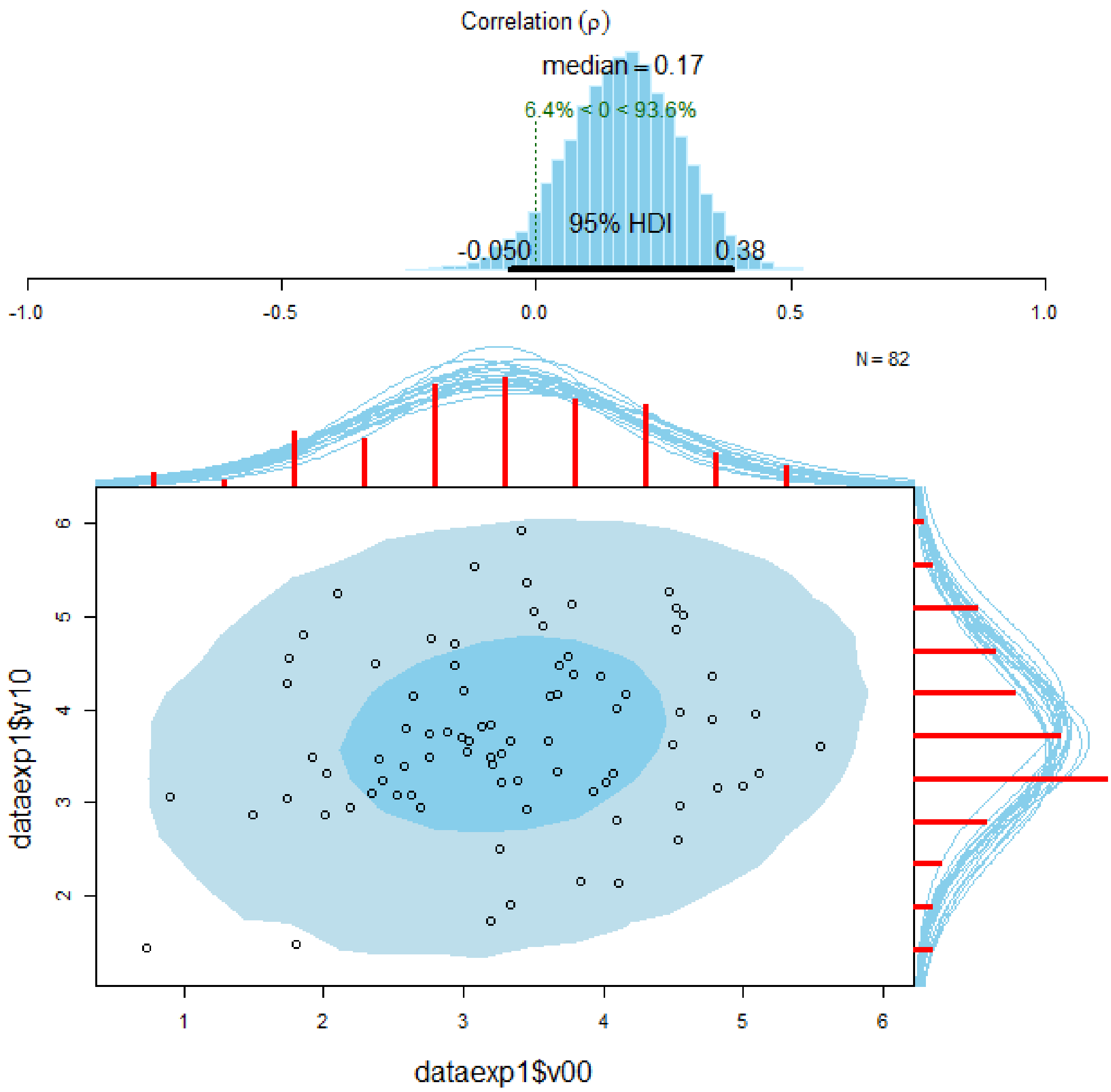


Figure 119. Visualisation of the results of the Bayesian correlational analysis for experimental condition V_{00} and V_{01} with associated posterior high density credible intervals and marginal posterior predictive plots.

This upper panel of the plot displays the posterior distribution for the correlation ρ (rho) with its associated 95% HDI. In addition, the lower panel of the plot shows the original empirical data with superimposed posterior predictive distributions. The posteriors predictive distributions allow to predict new data and can also be utilised to assess the model fit. It can be seen that the model fits the data reasonably well. The two histograms (in red) visualise the marginal distributions of the experimental data. The dark-blue ellipse encompasses the 50% highest density region and the light-blue ellipse spans the 95% high density region, thereby providing intuitive visual insights into the probabilistic distribution of the data (Friendly et al., 2013; Hollowood, 2016). The Bayesian analysis provides much more detailed and precise information compared to the classical frequentist Pearsonian approach.

We repeated the same analysis for experimental condition V_{10} and V_{11}. Pearson's r was again nonsignificant, $r = 0.02$, $p = 0.86$, 95% *CI* [-0.20, 0.24], indicating that the correlation between experimental conditions V_{10} and V_{11} is statistically non-significant, i.e., H_0 cannot be rejected. The estimated Bayesian correlation was $\rho = 0.20$, 95% HDI [-0.03, 0.41]. The analysis indicated that the correlation between condition V_{00} vs. V_{01} is > 0 by a probability of 0.958 (and < 0 by a probability of 0.042). A visual summary of the results is provided in Figure 129 and provided a quantitative overview of the results.

Table 53

Numerical summary for all parameters associated with experimental condition V_{01} and V_{11} and their corresponding 95% posterior high density credible intervals.

Measures	mean	sd	HDIlo	HDIup	%<comp	%>comp
rho	0.198	0.109	-0.017	0.409	0.038	0.962
mu[1]	7.218	0.127	6.966	7.464	0.000	1.000
mu[2]	6.685	0.120	6.447	6.921	0.000	1.000
sigma[1]	1.102	0.100	0.909	1.304	0.000	1.000
sigma[2]	1.045	0.095	0.861	1.232	0.000	1.000
nu	34.731	27.521	3.500	90.205	0.000	1.000
xy_pred[1]	7.215	1.175	4.917	9.561	0.000	1.000
xy_pred[2]	6.686	1.113	4.473	8.875	0.000	1.000

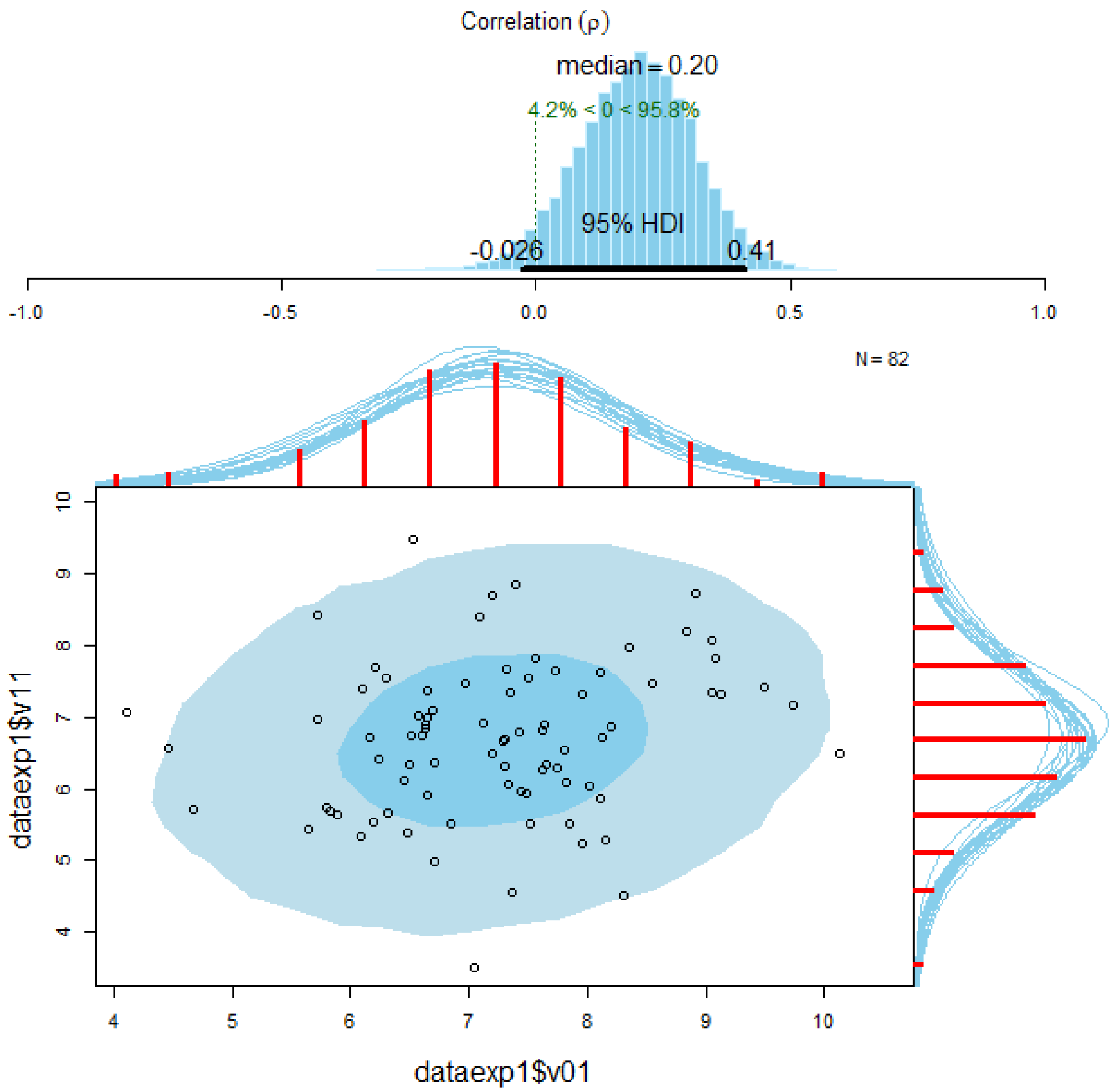


Figure 120. Visualisation of the results of the Bayesian correlational analysis for experimental condition V_{10} and V_{11} with associated posterior high density credible intervals and marginal posterior predictive plots.

Appendix C Experiment 2

Appendix C1 Skewness and kurtosis

```
> skewness(dataexp2)
        v00         v01         v10         v11 
 0.05521842  0.26098541 -0.19099235 -0.08011161 

> kurtosis(dataexp2)
     v00      v01      v10      v11 
2.529584 2.813996 3.338351 3.166635 
```

Appendix C2 Anscombe-Glynn kurtosis tests (Anscombe & Glynn, 1983)

data: dataexp2$v00

kurt = 2.52960, z = -0.65085, p-value = 0.5151

alternative hypothesis: kurtosis is not equal to 3

---

data: dataexp2$v01

kurt = 2.81400, z = 0.02739, p-value = 0.9781

alternative hypothesis: kurtosis is not equal to 3

---

data: dataexp2$v10

kurt = 3.33840, z = 0.92903, p-value = 0.3529

alternative hypothesis: kurtosis is not equal to 3

---

data: dataexp2$v11

kurt = 3.16660, z = 0.67032, p-value = 0.5027

alternative hypothesis: kurtosis is not equal to 3

D'Agostino skewness tests (D'Agostino, 1970)

data: dataexp2$v00

skew = 0.055198, z = 0.194460, p-value = 0.8458

alternative hypothesis: data have a skewness

---

data: dataexp2$v01

skew = 0.26100, z = 0.90906, p-value = 0.3633

alternative hypothesis: data have a skewness

---

data: dataexp2$v10

skew = -0.19101, z = -0.66895, p-value = 0.5035

alternative hypothesis: data have a skewness

---

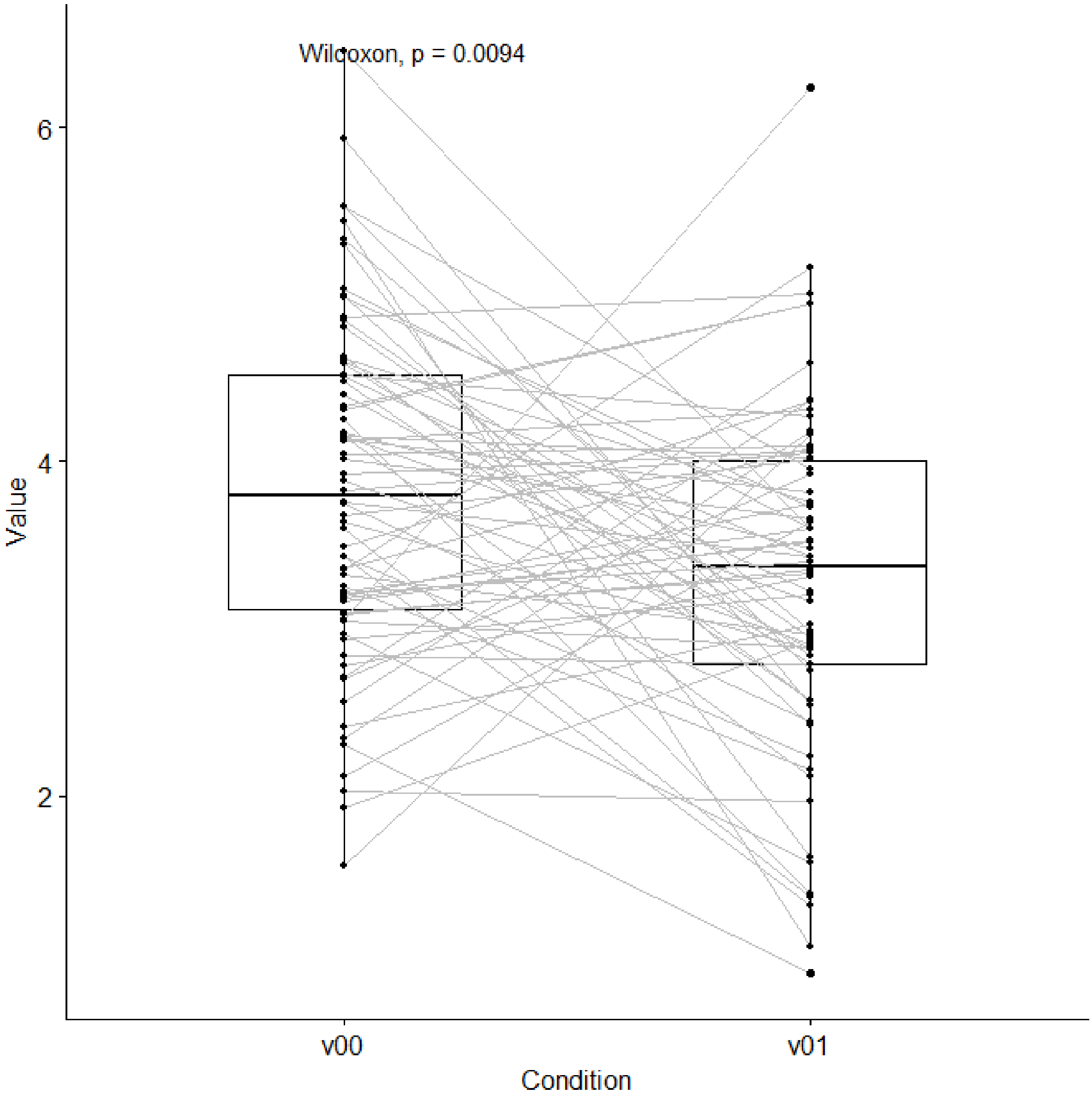
data: dataexp2$v11

skew = -0.080075, z = -0.281940, p-value = 0.778

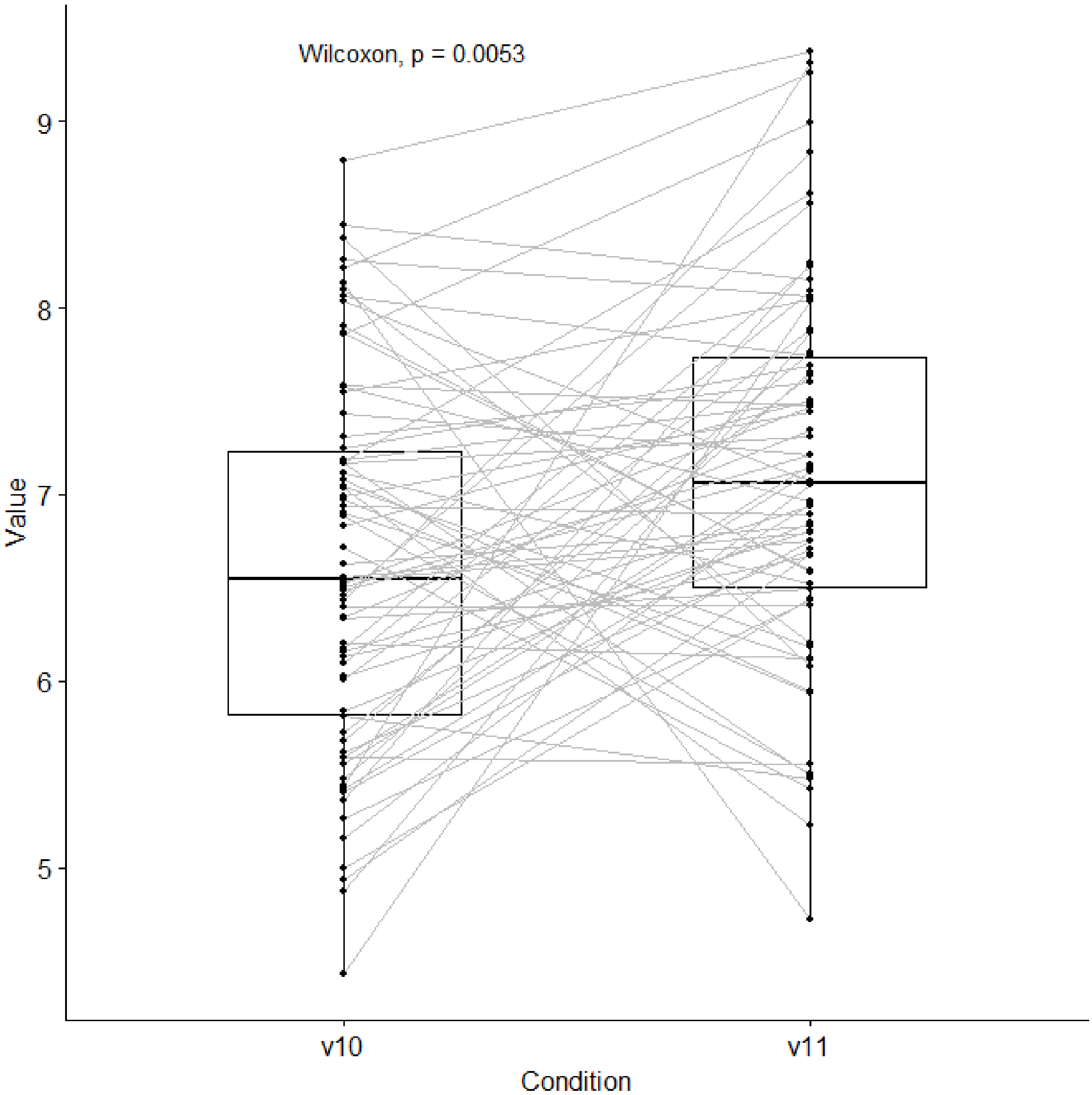
alternative hypothesis: data have a skewness

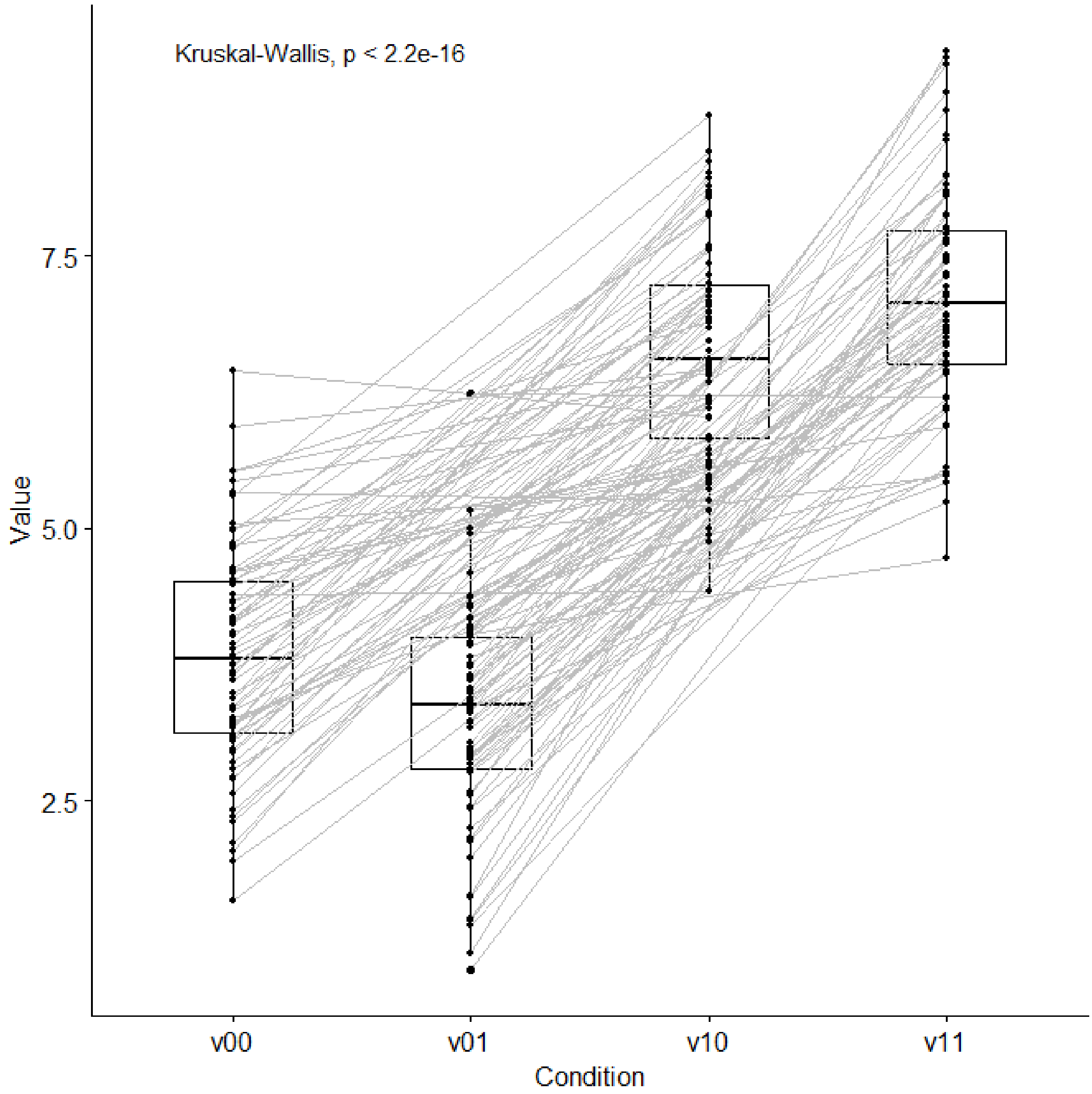
Appendix C3 Connected boxplots

Plots are based on the R library "`ggpubr`"[244] which provides numerous functions for elegant data visualization.



[244] Available on CRAN: https://cran.r-project.org/web/packages/ggpubr/ggpubr.pdf


Wilcoxon, p = 0.0053
9
8
7
6
5
Value
v10
v11
Condition


Kruskal-Wallis, p < 2.2e-16
7.5
5.0
2.5
Value
v00
v01
v10
v11
Condition

Appendix C4 MCMC convergence diagnostics for experimental condition V_{00} vs. V_{01}

This appendix contains the MCMC convergence diagnostic (i.e., MCSE, ESS, Rhat) for all parameters. The associated graphics show the trace plot and the density plot.

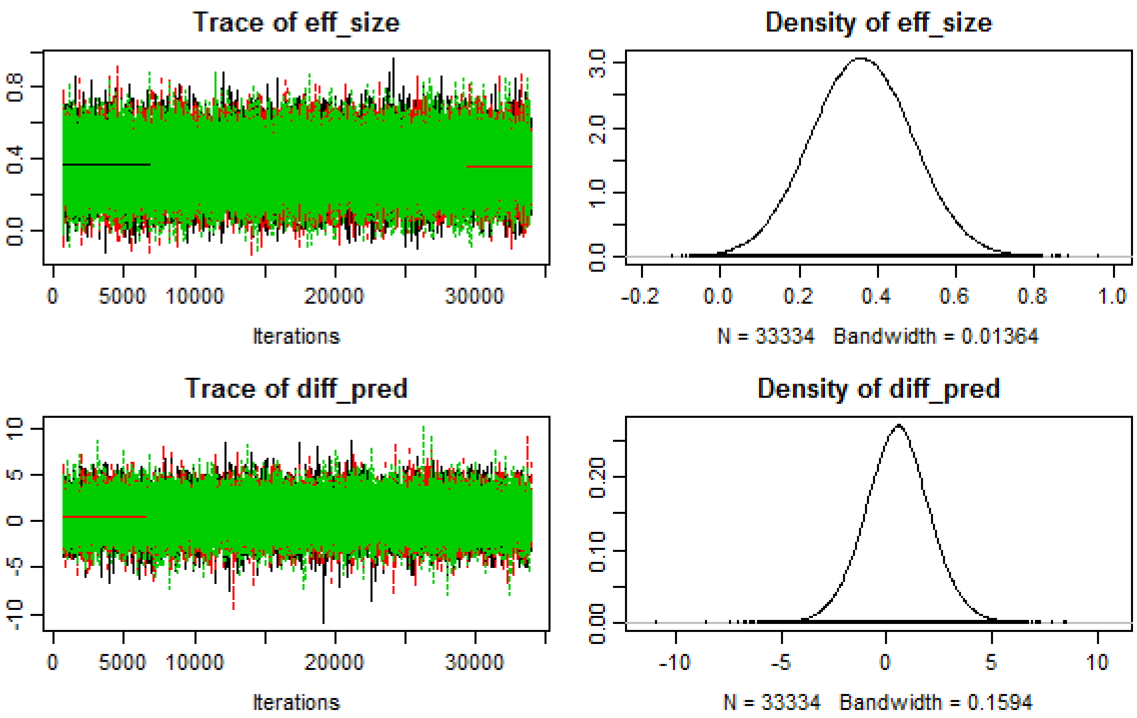
```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
             mean     sd mcmc_se  n_eff Rhat
mu_diff     0.523  0.183   0.001  61589    1
sigma_diff  1.467  0.143   0.001  45052    1
nu         37.892 30.417   0.216  19809    1
eff_size    0.360  0.129   0.001  61073    1
diff_pred   0.533  1.571   0.005 100001    1
```

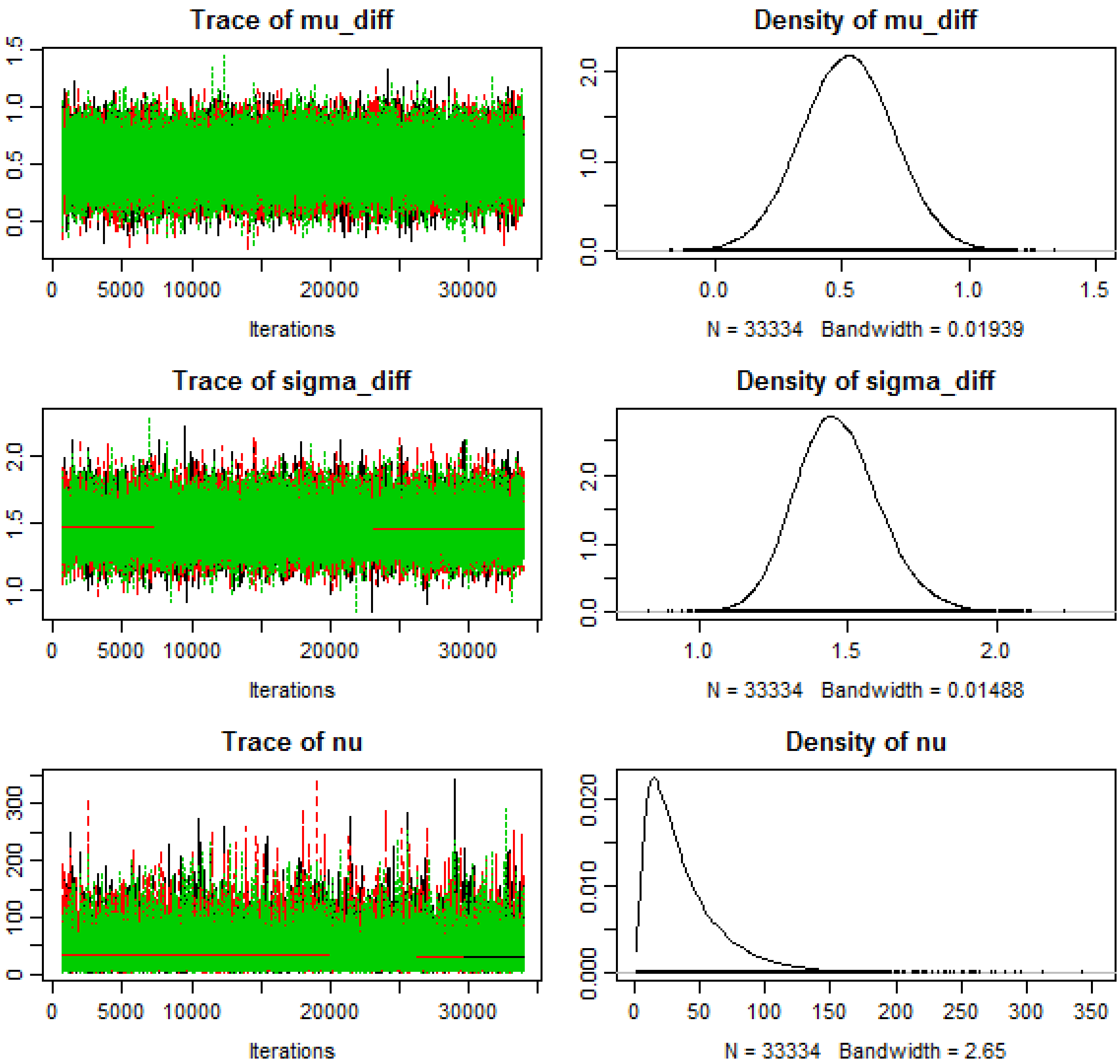
Model parameters:

- μ_Δ (mu_diff): The mean pairwise difference between experimental conditions
- σ_Δ (sigma_diff): the scale of the pairwise difference (a consistent estimate of SD when nu is large)
- v (nu): The degrees-of-freedom for the bivariate *t* distribution fitted to the pairwise difference
- δ (eff_size): the effect size calculated as $(\mu_\Delta - 0)/\sigma_\Delta$.
- $\mu_{\Delta pred}$ (diff_pred): predicted distribution for a new datapoint generated as the pairwise difference between experimental conditions

Convergence diagnostics:

- mcmc_se (Monte Carlo Standard Error, MCSE): The estimated standard error of the MCMC approximation of the mean.
- n_eff (Effective Sample Size, ESS): A crude measure of effective MCMC sample size.
- Rhat (Shrink factor, $\hat{R}$): the potential scale reduction factor (at convergence, $\hat{R} \approx 1$).


Trace of eff_size
Iterations
Density of eff_size
N = 33334 Bandwidth = 0.01364
Trace of diff_pred
Iterations
Density of diff_pred
N = 33334 Bandwidth = 0.1594



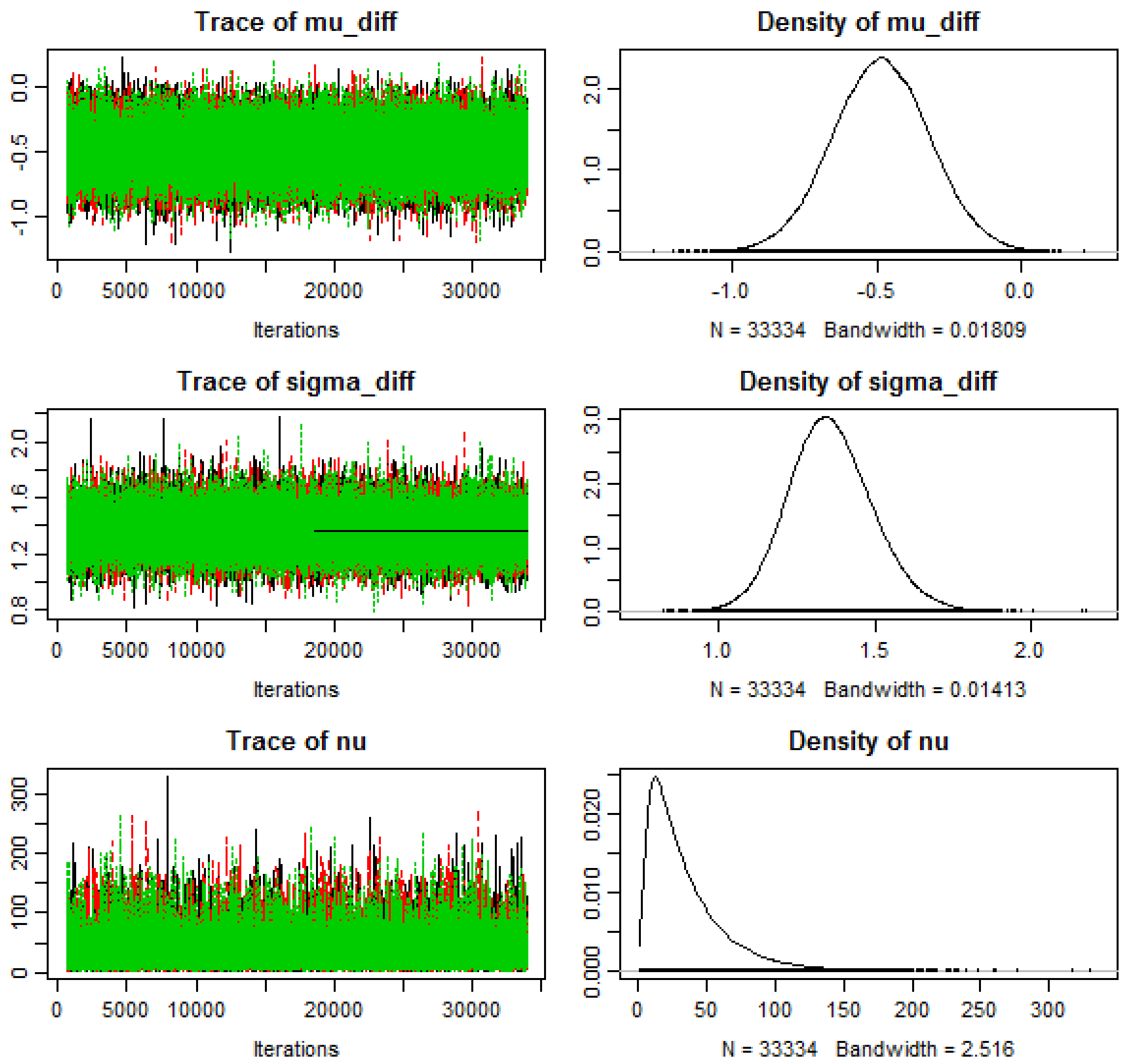
Trace of mu_diff
Iterations
Density of mu_diff
N = 33334 Bandwidth = 0.01939
Trace of sigma_diff
Iterations
Density of sigma_diff
N = 33334 Bandwidth = 0.01488
Trace of nu
Iterations
Density of nu
N = 33334 Bandwidth = 2.65

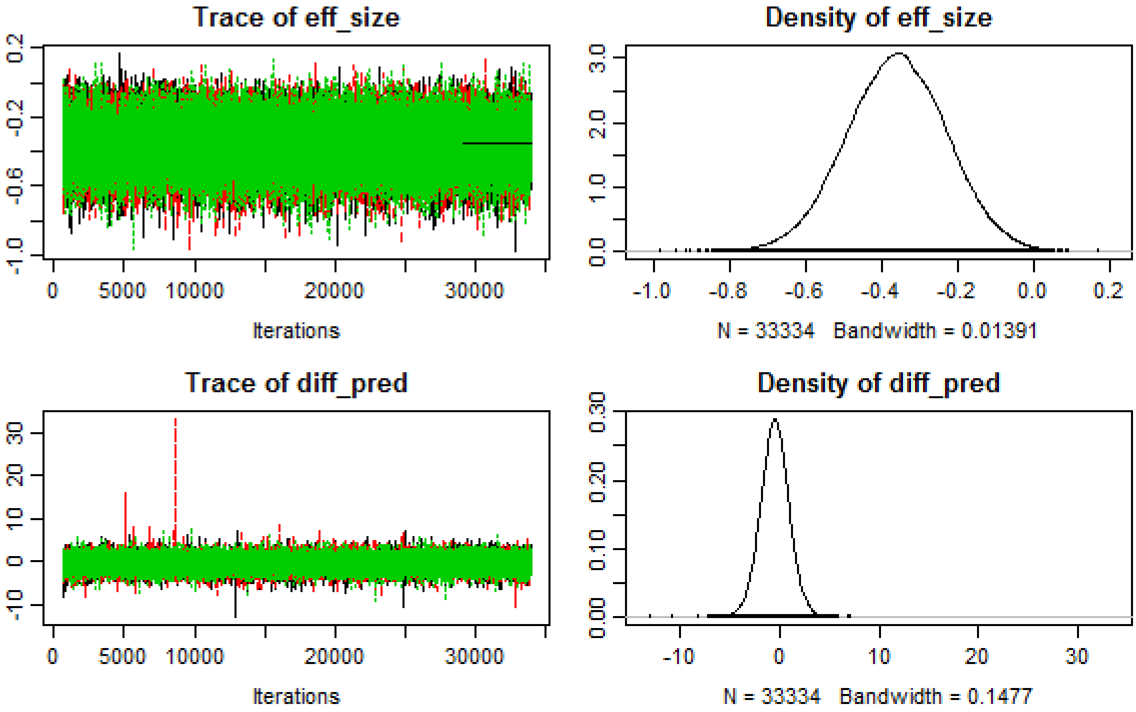
Appendix C5 MCMC convergence diagnostics for xperimental condition V_{10} vs V_{11}

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
              mean     sd mcmc_se  n_eff Rhat
mu_diff     -0.485  0.171   0.001  60590    1
sigma_diff   1.358  0.137   0.001  42080    1
nu          35.134 28.790   0.206  19744    1
eff_size    -0.361  0.131   0.001  59362    1
diff_pred   -0.485  1.461   0.005 100001    1
```

Model parameters:

- μ_Δ (mu_diff): The mean pairwise difference between experimental conditions
- σ_Δ (sigma_diff): the scale of the pairwise difference (a consistent estimate of SD when nu is large)
- ν (nu): The degrees-of-freedom for the bivariate *t* distribution fitted to the pairwise difference
- δ (eff_size): the effect size calculated as $(\mu_\Delta - 0)/\sigma_\Delta$.
- $\mu_{\Delta pred}$ (diff_pred): predicted distribution for a new datapoint generated as the pairwise difference between experimental conditions


Trace of mu_diff
Iterations
Density of mu_diff
N = 33334 Bandwidth = 0.01809
Trace of sigma_diff
Iterations
Density of sigma_diff
N = 33334 Bandwidth = 0.01413
Trace of nu
Iterations
Density of nu
N = 33334 Bandwidth = 2.516


Trace of eff_size
Iterations
Density of eff_size
N = 33334 Bandwidth = 0.01391
Trace of diff_pred
Iterations
Density of diff_pred
N = 33334 Bandwidth = 0.1477

Appendix C6 Visualisation of MCMC: 3-dimensional scatterplot with associated concentration eclipse

"*I know of no person or group that is taking nearly adequate advantage of the graphical potentialities of the computer.*"

~ John Tukey

R is equipped with a powerful computer graphic system which can be extended with additional libraries, e.g., OpenGL (Open Graphics Library; Hearn & Baker, 2004; Murdoch, 2001). The following three-dimensional visualisations was created with the R package "scatterplot3d" (Ligges & Mächler, 2003) which utilises Open GL. The graphic depicts the relationship between experimental conditions, i.e., V_{00} versus V_{01}, based on 1200 steps extracted from the MCMC samples. An interactive fullscreen-version which allows closer inspection of the data is available under the following URL: http://irrational-decisions.com/phd-thesis/scatterplot3d-openGL.mp4

The MCMC dataset and the R code are also available online: http://irrational-decisions.com/?page_id=2100

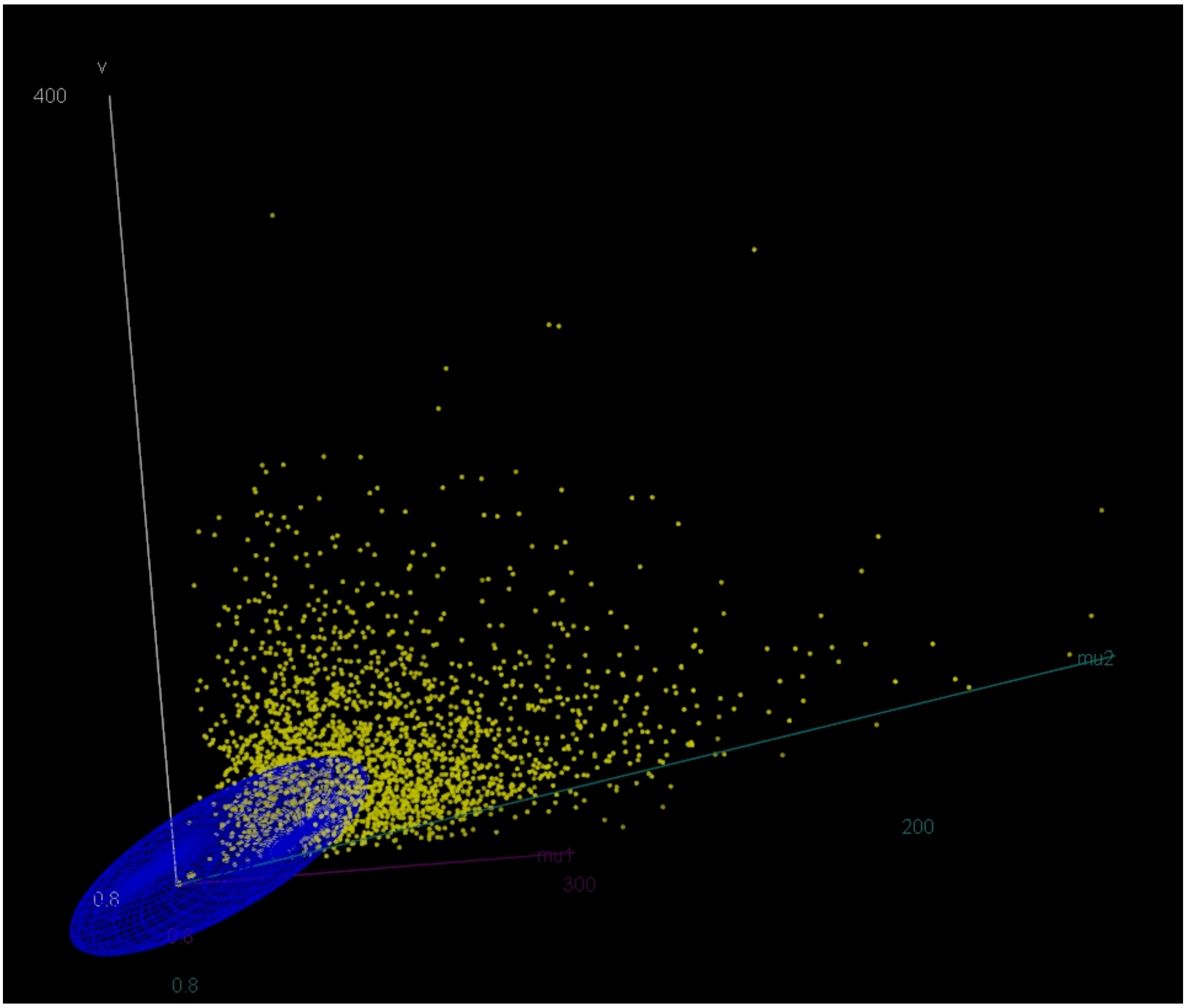


Figure 121. 3D scatterplot of the MCMC dataset with 50% concentration ellipsoid visualising the relation between μ_1 (V_{00}) and μ_2 (V_{01}), and v in 3-dimensional parameter space.

Ellipsoids are an intuitive way to understanding of multivariate relationships (Kruschke, 2014). Ellipsoids provide a visual summary for the means, the standard deviations, and correlations in 3-dimensional data space (Friendly et al., 2013).

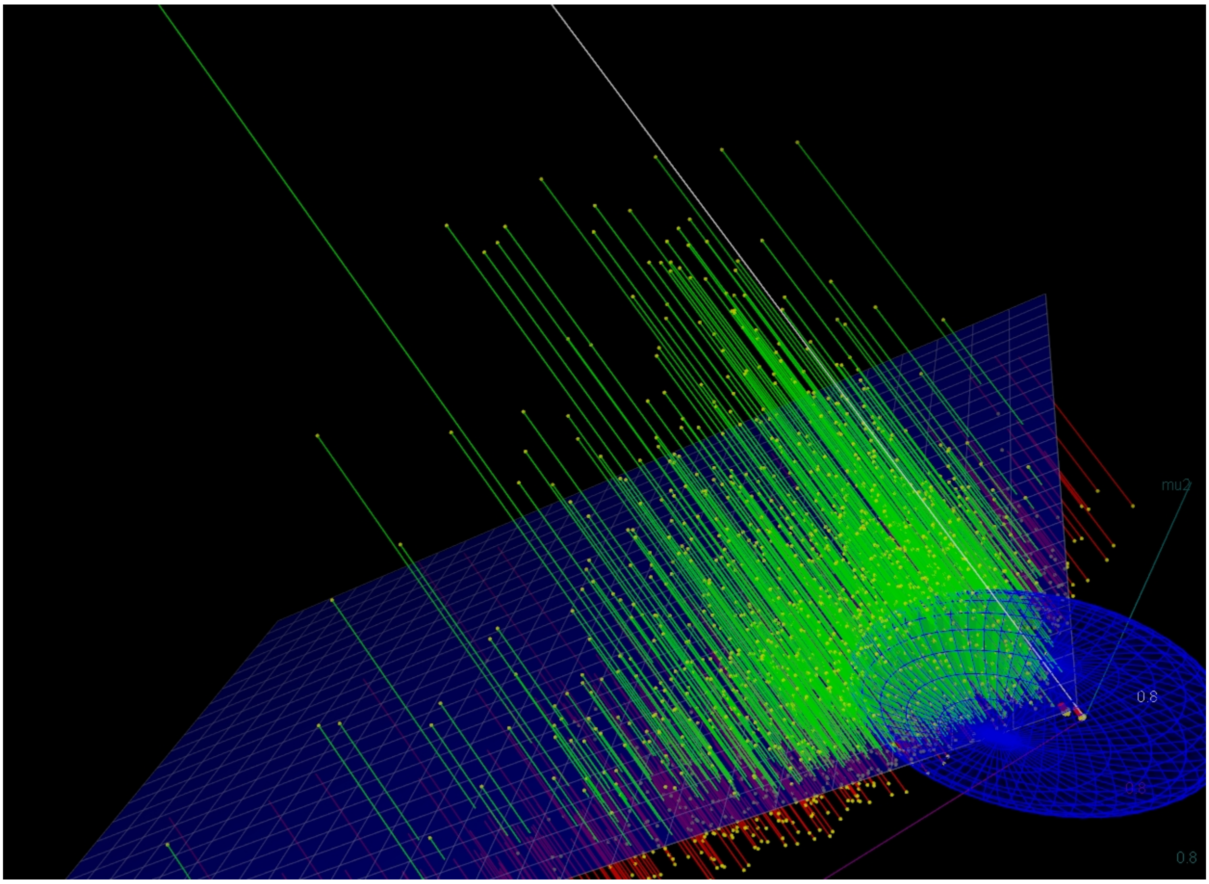


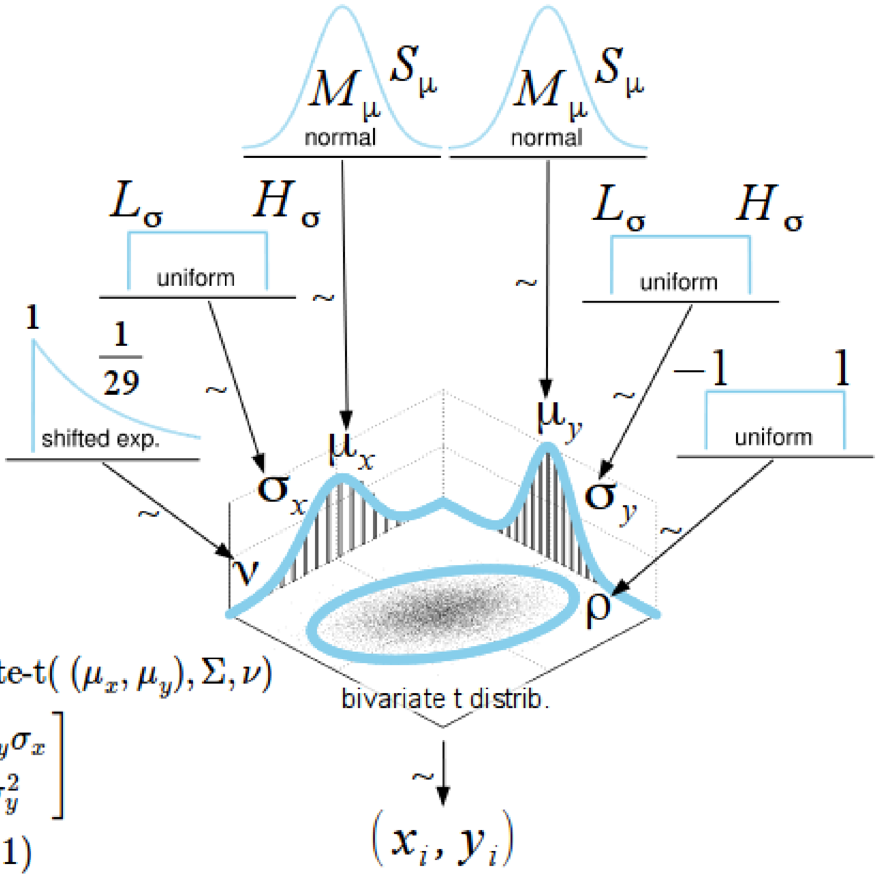
Figure 122. 3D scatterplot (with regression plane) of MCMC dataset with increased zoom-factor in order to emphasize the concentration of the values of θ.

```
mcmcExp2 <- readXL("C:/Users/cgermann/Documents/BEST/mcmc-exp2.xlsx",
  rownames=FALSE, header=TRUE, na="", sheet="mcmc-chain-exp2-with-header",
  stringsAsFactors=TRUE)
library(rgl, pos=14)
library(nlme, pos=15)
library(mgcv, pos=15)
scatter3d(v~mu1+mu2, data=mcmcExp2, surface=TRUE, bg="black", axis.scales=TRUE,
grid=TRUE, ellipsoid=TRUE, model.summary=TRUE)
```

Code 9. R commander code for 3D scatterplot with concertation ellipsoid.

Appendix C7 Correlational analysis

Appendix C7.1 Hierarchical Bayesian model



$$(x_i, y_i) \sim \text{Bivariate-t}(\,(\mu_x, \mu_y), \Sigma, \nu)$$

$$\Sigma = \begin{bmatrix} \sigma_x^2 & \rho\sigma_y\sigma_x \\ \rho\sigma_y\sigma_x & \sigma_y^2 \end{bmatrix}$$

$$\rho \sim \text{Uniform}(-1, 1)$$

$$\mu_x, \mu_y \sim \text{Normal}(M_\mu, S_\mu)$$

$$\sigma_x, \sigma_y \sim \text{Uniform}(L_\sigma, H_\sigma)$$

$$\nu \sim \text{ShiftedExp}(\tfrac{1}{29}\,, \text{shift} = 1)$$

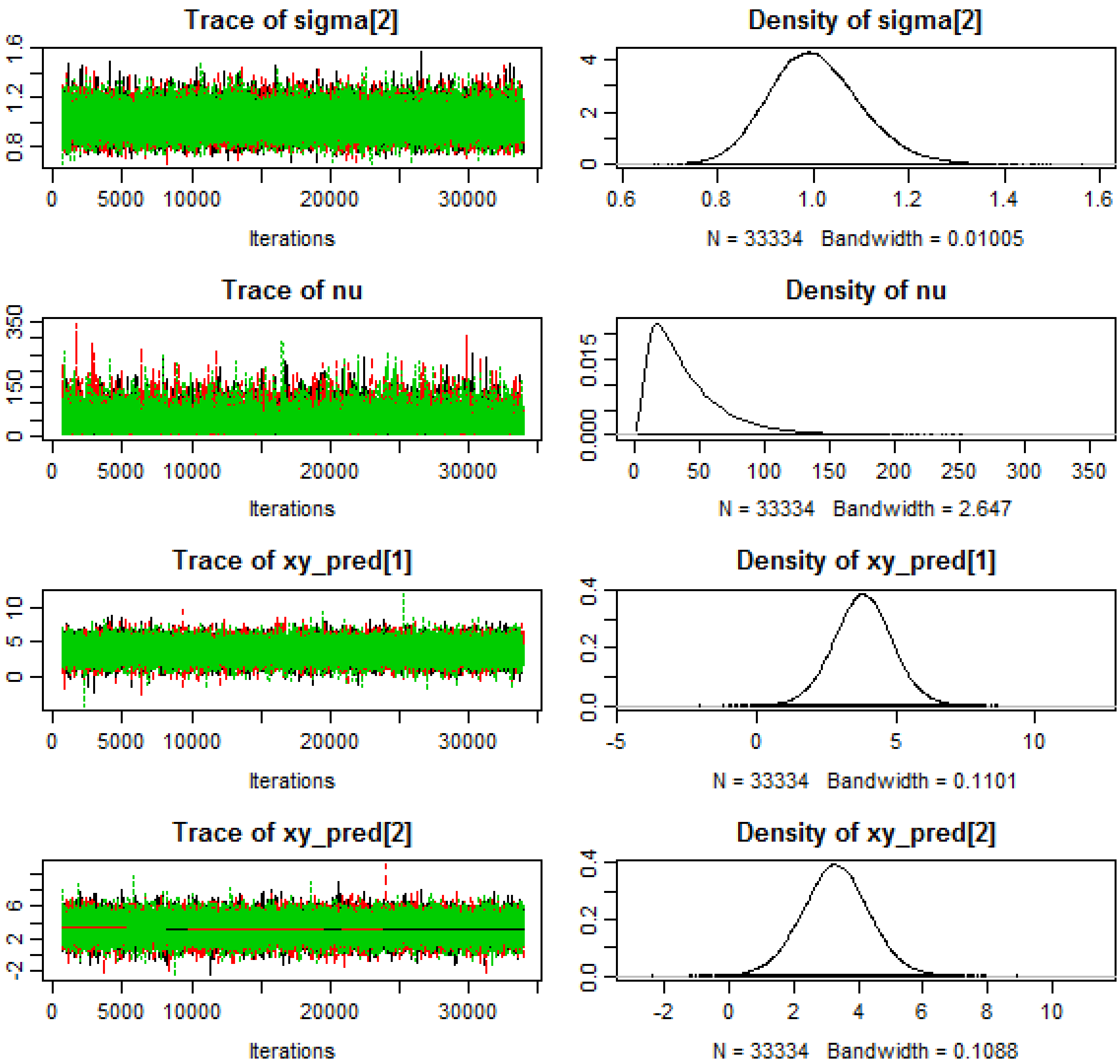
The associated hierarchical Bayesian model is described in greater detail in the analysis section of Experiment 1.

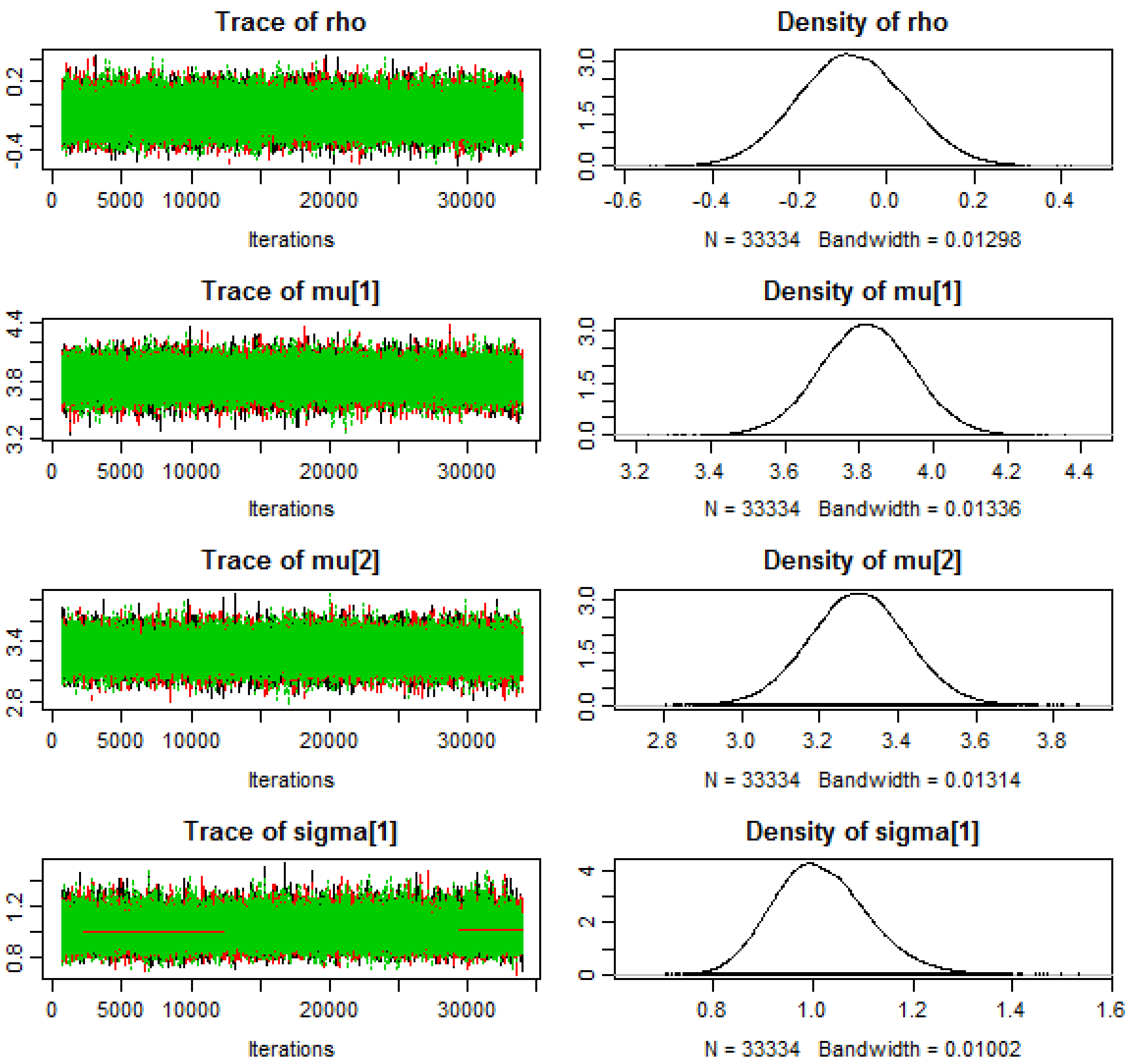
Appendix C7.2 Convergence diagnostics for the Bayesian correlational analysis (V_{10} vs. V_{11})

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
              mean     sd mcmc_se  n_eff  Rhat
rho         -0.079  0.122   0.001  58760 1.000
mu[1]        3.819  0.126   0.001  58238 1.000
mu[2]        3.298  0.125   0.001  60951 1.000
sigma[1]     1.017  0.096   0.000  48272 1.000
sigma[2]     1.005  0.097   0.000  46355 1.000
nu          39.910 29.999   0.210  21090 1.001
xy_pred[1]   3.817  1.071   0.003 100002 1.000
xy_pred[2]   3.301  1.064   0.003  98680 1.000
```

Model parameters:

- ρ (rho): The correlation between experimental condition V_{00} and V_{10}
- μ_1 (mu[1]): The mean of V_{00}
- σ_1 (sigma[1]): The scale of V_{00}, a consistent estimate of SD when nu is large.
- μ_2 (mu[2]): the mean of V_{10}
- σ_1 (sigma[2]): the scale of V_{10}
- v (nu): The degrees-of-freedom for the bivariate *t* distribution
- xy_pred[1]: The posterior predictive distribution of V_{00}
- xy_pred[2]: The posterior predictive distribution of V_{10}


Trace of sigma[2]
Iterations
Density of sigma[2]
N = 33334 Bandwidth = 0.01005
Trace of nu
Iterations
Density of nu
N = 33334 Bandwidth = 2.647
Trace of xy_pred[1]
Iterations
Density of xy_pred[1]
N = 33334 Bandwidth = 0.1101
Trace of xy_pred[2]
Iterations
Density of xy_pred[2]
N = 33334 Bandwidth = 0.1088



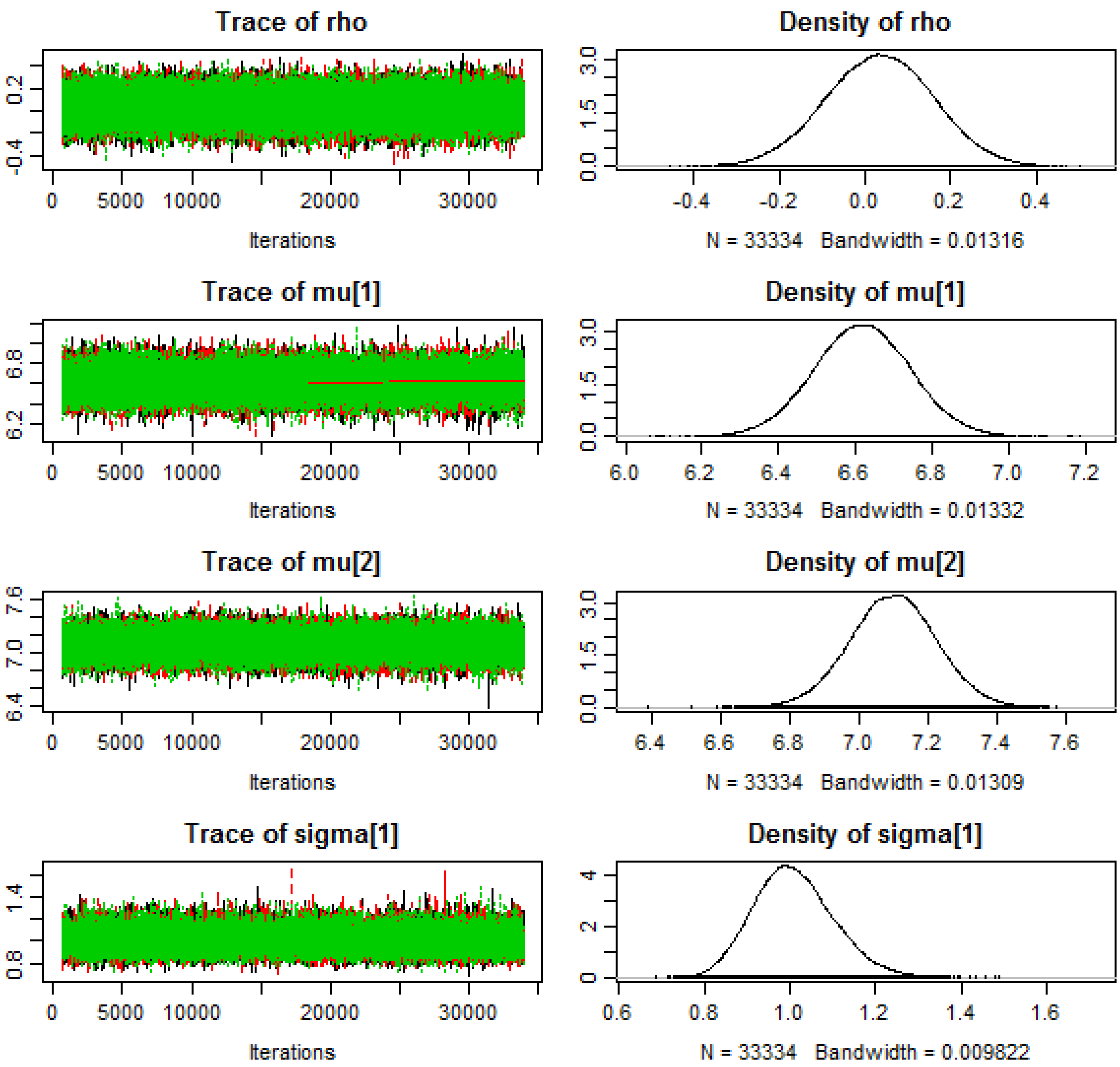
Trace of rho
Density of rho
Iterations
N = 33334 Bandwidth = 0.01298
Trace of mu[1]
Density of mu[1]
Iterations
N = 33334 Bandwidth = 0.01336
Trace of mu[2]
Density of mu[2]
Iterations
N = 33334 Bandwidth = 0.01314
Trace of sigma[1]
Density of sigma[1]
Iterations
N = 33334 Bandwidth = 0.01002

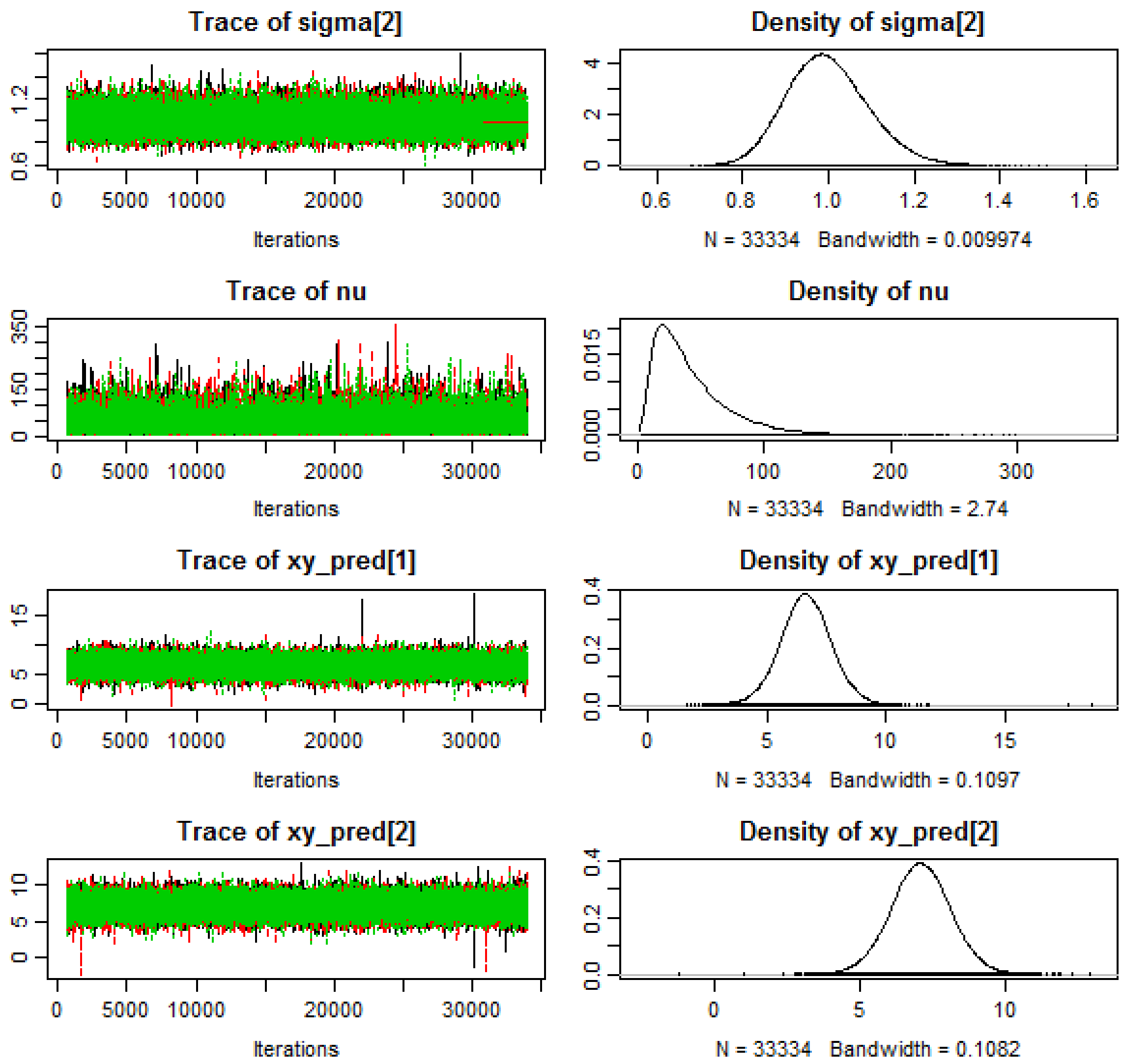
Appendix C7.3 Convergence diagnostics for the Bayesian correlational analysis (V_{10} and V_{11})

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
             mean     sd mcmc_se n_eff Rhat
rho         0.034  0.124   0.001 61483    1
mu[1]       6.617  0.126   0.001 61561    1
mu[2]       7.098  0.124   0.000 61224    1
sigma[1]    1.009  0.094   0.000 49525    1
sigma[2]    0.999  0.095   0.000 47846    1
nu         42.025 30.704   0.211 21292    1
xy_pred[1]  6.619  1.069   0.003 99485    1
xy_pred[2]  7.101  1.054   0.003 97846    1
```

Model parameters:

- ρ (rho): The correlation between experimental condition V_{00} and V_{10}
- μ_1 (mu[1]): The mean of V_{00}
- σ_1 (sigma[1]): The scale of V_{00}, a consistent estimate of SD when nu is large.
- μ_2 (mu[2]): the mean of V_{10}
- σ_1 (sigma[2]): the scale of V_{10}
- ν (nu): The degrees-of-freedom for the bivariate *t* distribution
- xy_pred[1]: The posterior predictive distribution of V_{00}
- xy_pred[2]: The posterior predictive distribution of V_{10}


Trace of rho
Iterations
Density of rho
N = 33334 Bandwidth = 0.01316
Trace of mu[1]
Iterations
Density of mu[1]
N = 33334 Bandwidth = 0.01332
Trace of mu[2]
Iterations
Density of mu[2]
N = 33334 Bandwidth = 0.01309
Trace of sigma[1]
Iterations
Density of sigma[1]
N = 33334 Bandwidth = 0.009822



Trace of sigma[2]
Iterations
Density of sigma[2]
N = 33334 Bandwidth = 0.009974
Trace of nu
Iterations
Density of nu
N = 33334 Bandwidth = 2.74
Trace of xy_pred[1]
Iterations
Density of xy_pred[1]
N = 33334 Bandwidth = 0.1097
Trace of xy_pred[2]
Iterations
Density of xy_pred[2]
N = 33334 Bandwidth = 0.1082

Appendix C7.4 Pearson's product-moment correlation between experimental condition V00 vs. V10

```
        Pearson's product-moment correlation

data:  v00 and v01
t = -0.65285, df = 68, p-value = 0.5161
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.3081814  0.1590001
sample estimates:
        cor
-0.07892249
```

```
             mean     sd  HDIlo  HDIup %<comp %>comp
rho        -0.079  0.122 -0.315  0.163  0.740  0.260
mu[1]       3.819  0.126  3.572  4.069  0.000  1.000
mu[2]       3.298  0.125  3.055  3.545  0.000  1.000
sigma[1]    1.017  0.096  0.834  1.209  0.000  1.000
sigma[2]    1.005  0.097  0.821  1.198  0.000  1.000
nu         39.910 29.999  3.967 99.213  0.000  1.000
xy_pred[1]  3.817  1.071  1.678  5.924  0.001  0.999
xy_pred[2]  3.301  1.064  1.176  5.391  0.002  0.998
```

Model parameters:

- ρ (rho): The correlation between experimental condition V_{00} and V_{10}
- μ_1 (mu[1]): The mean of V_{00}
- σ_1 (sigma[1]): The scale of V_{00}, a consistent estimate of SD when nu is large.
- μ_2 (mu[2]): the mean of V_{10}
- σ_1 (sigma[2]): the scale of V_{10}
- ν (nu): The degrees-of-freedom for the bivariate *t* distribution
- xy_pred[1]: The posterior predictive distribution of V_{00}
- xy_pred[2]: The posterior predictive distribution of V_{10}

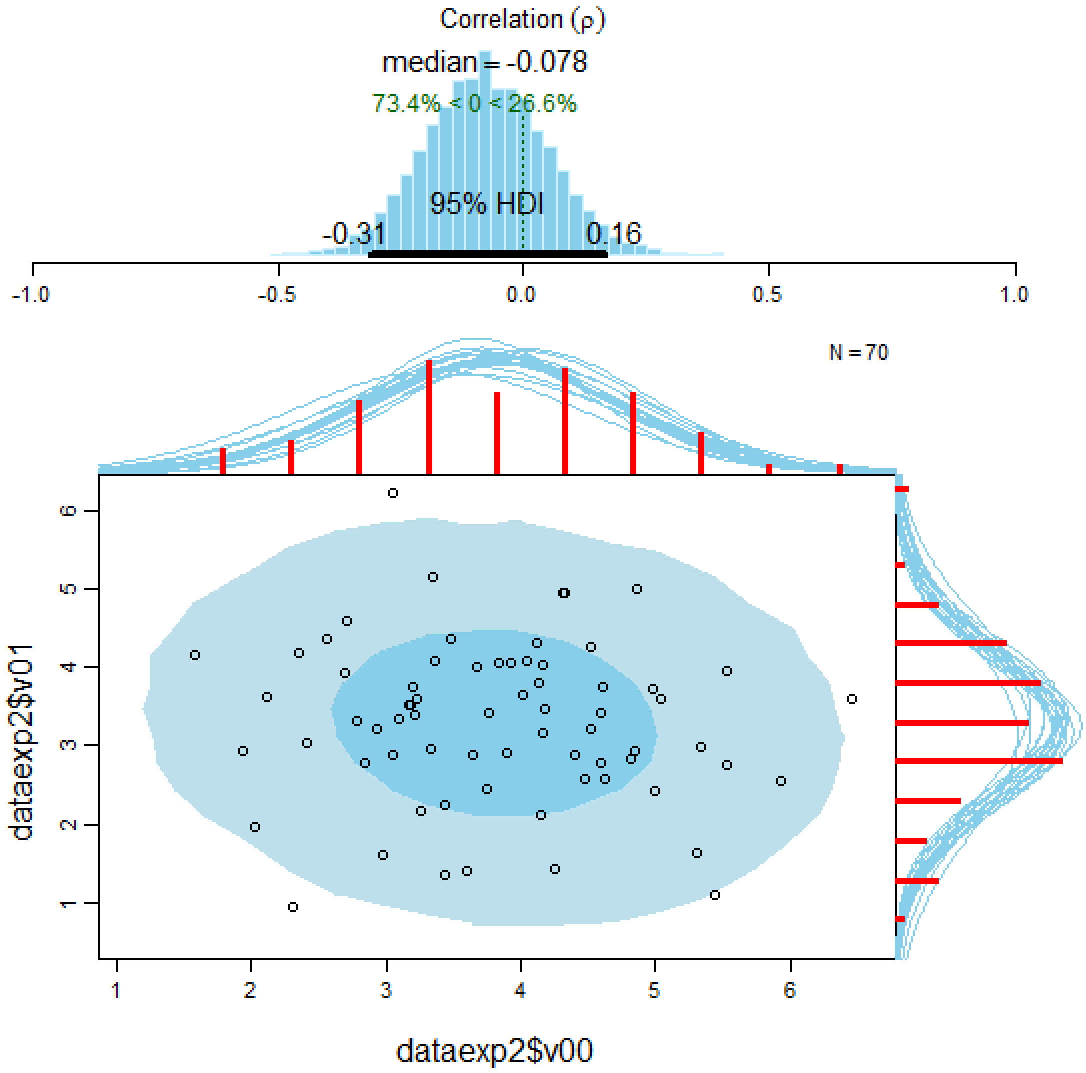


Figure 123. Visualisation of the results of the Bayesian correlational analysis for experimental condition V_{00} and V_{01} with associated posterior high density credible intervals and marginal posterior predictive plots.

This upper panel of the plot displays the posterior distribution for the correlation ρ (rho) with its associated 95% HDI. In addition, the lower panel of the plot shows the original empirical data with superimposed posterior predictive distributions. The posteriors predictive distributions allow to predict new data and can also be utilised to assess the model fit. It can be seen that the model fits the data reasonably well. The two histograms (in red) visualise the marginal distributions of the experimental data. The dark-blue ellipse encompasses the 50% highest density region and the light-blue ellipse spans the 95% high density region, thereby providing intuitive visual insights into the probabilistic distribution of the data (Hollowood, 2016). The Bayesian analysis provides much more detailed and precise information compared to the classical frequentist Pearsonian approach.

Appendix C7.5 Pearson's product-moment correlations between experimental conditions V_{01} vs V_{11}

```
        Pearson's product-moment correlation


data:  v10 and v11

t = 0.33564, df = 68, p-value = 0.7382

alternative hypothesis: true correlation is not equal to 0

95 percent confidence interval:

 -0.1961796  0.2730340

sample estimates:

       cor

0.04066911
```

Table 54

Numerical summary for all parameters associated with experimental condition V_{10} and V_{01} and their corresponding 95% posterior high density credible intervals.

	mean	sd	HDIlo	HDIup	%<comp	%>comp
rho	0.034	0.124	-0.210	0.275	0.39	0.61
mu[1]	6.617	0.126	6.368	6.863	0.00	1.00
mu[2]	7.098	0.124	6.855	7.341	0.00	1.00
sigma[1]	1.009	0.094	0.831	1.194	0.00	1.00
sigma[2]	0.999	0.095	0.821	1.191	0.00	1.00
nu	42.025	30.704	4.393	102.736	0.00	1.00
xy_pred[1]	6.619	1.069	4.491	8.726	0.00	1.00
xy_pred[2]	7.101	1.054	4.980	9.149	0.00	1.00

Note. 'HDIlo' and 'HDIup' are the limits of a 95% HDI credible interval.

'%<comp' and '%>comp' are the probabilities of the respective parameter being smaller or larger than 0.

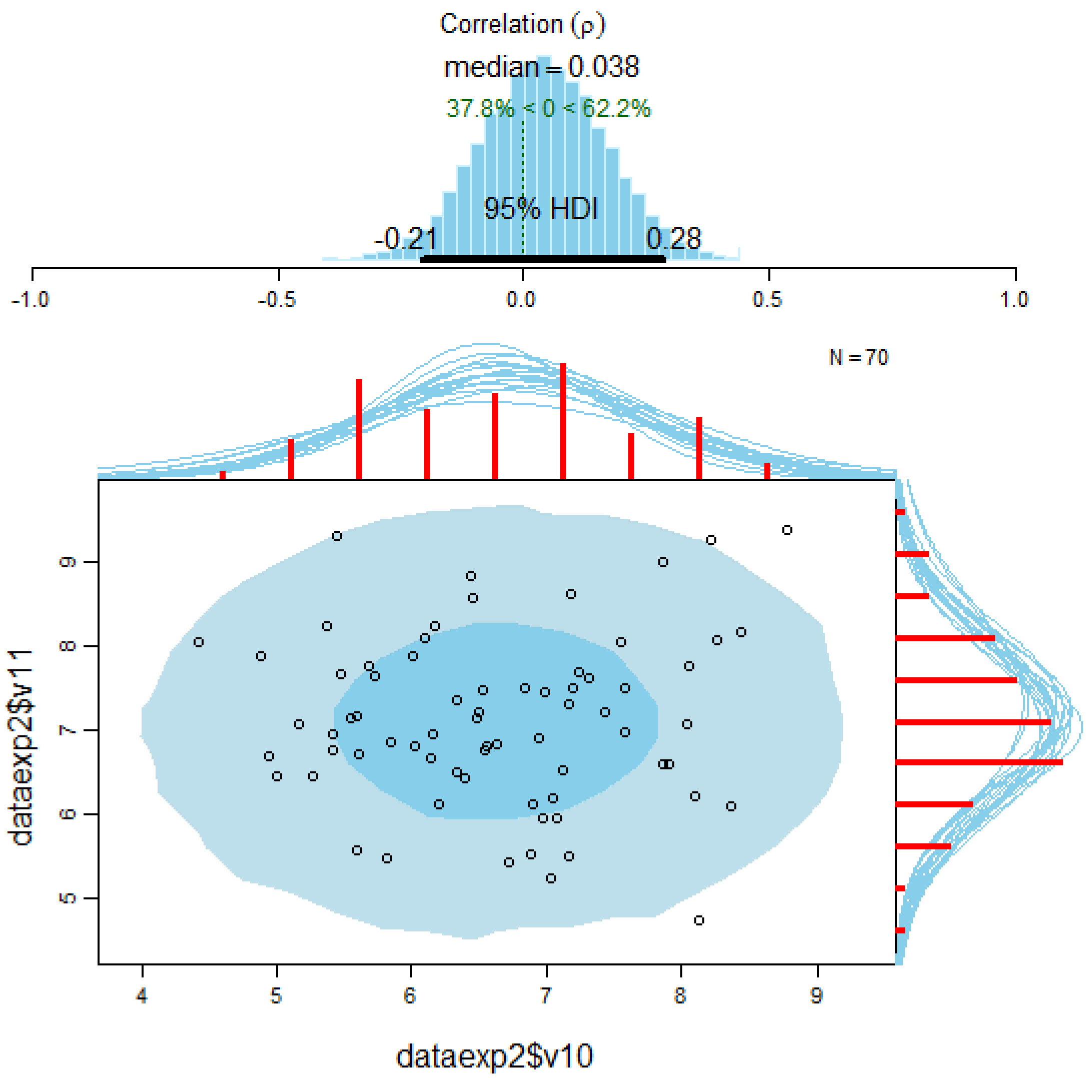


Figure 124. Visualisation of the results of the Bayesian correlational analysis for experimental condition V_{10} and V_{11} with associated posterior high density credible intervals and marginal posterior predictive plots.

Appendix C8 JAGS model code for the correlational analysis

```
# Model code for the Bayesian alternative to Pearson's correlation
test.
# (Bååth, 2014)
require(rjags)
#(Plummer, 2016)
#download data from webserver and import as table
Dataexp2 <-
  read.table("http://www.irrational-decisions.com/phd-
thesis/dataexp2.csv", header=TRUE, sep=",", na.strings="NA",
dec=".", strip.white=TRUE)

# Setting up the data
x <- dataexp1$v01
y <- dataexp1$v11
xy <- cbind(x, y)

# The model string written in the JAGS language
model_string <- "model {
  for(i in 1:n) {
    xy[i,1:2] ~ dmt(mu[], prec[ , ], nu)
  }

  xy_pred[1:2] ~ dmt(mu[], prec[ , ], nu)
```

```
  # JAGS parameterizes the multivariate t using precision (inverse
of variance)
  # rather than variance, therefore here inverting the covariance
matrix.
  prec[1:2,1:2] <- inverse(cov[,])

  # Constructing the covariance matrix
  cov[1,1] <- sigma[1] * sigma[1]
  cov[1,2] <- sigma[1] * sigma[2] * rho
  cov[2,1] <- sigma[1] * sigma[2] * rho
  cov[2,2] <- sigma[2] * sigma[2]

  # Priors
  rho ~ dunif(-1, 1)
  sigma[1] ~ dunif(sigmaLow, sigmaHigh)
  sigma[2] ~ dunif(sigmaLow, sigmaHigh)
  mu[1] ~ dnorm(mean_mu, precision_mu)
  mu[2] ~ dnorm(mean_mu, precision_mu)
  nu <- nuMinusOne+1
  nuMinusOne ~ dexp(1/29)
}"

# Initializing the data list and setting parameters for the priors
# that in practice will result in flat priors on mu and sigma.
data_list = list(
  xy = xy,
  n = length(x),
```

```
  mean_mu = mean(c(x, y), trim=0.2) ,

  precision_mu = 1 / (max(mad(x), mad(y))^2 * 1000000),

  sigmaLow = min(mad(x), mad(y)) / 1000 ,

  sigmaHigh = max(mad(x), mad(y)) * 1000)


# Initializing parameters to sensible starting values helps the
convergence
# of the MCMC sampling. Here using robust estimates of the mean
(trimmed)
# and standard deviation (MAD).
inits_list = list(mu=c(mean(x, trim=0.2), mean(y, trim=0.2)),
rho=cor(x, y, method="spearman"),
                  sigma = c(mad(x), mad(y)), nuMinusOne = 5)


# The parameters to monitor.
params <- c("rho", "mu", "sigma", "nu", "xy_pred")


# Running the model
model <- jags.model(textConnection(model_string), data = data_list,
                    inits = inits_list, n.chains = 3, n.adapt=1000)
update(model, 500)
samples <- coda.samples(model, params, n.iter=5000)


# Inspecting the posterior
plot(samples)
summary(samples)
```

Appendix C9 Tests of Gaussianity

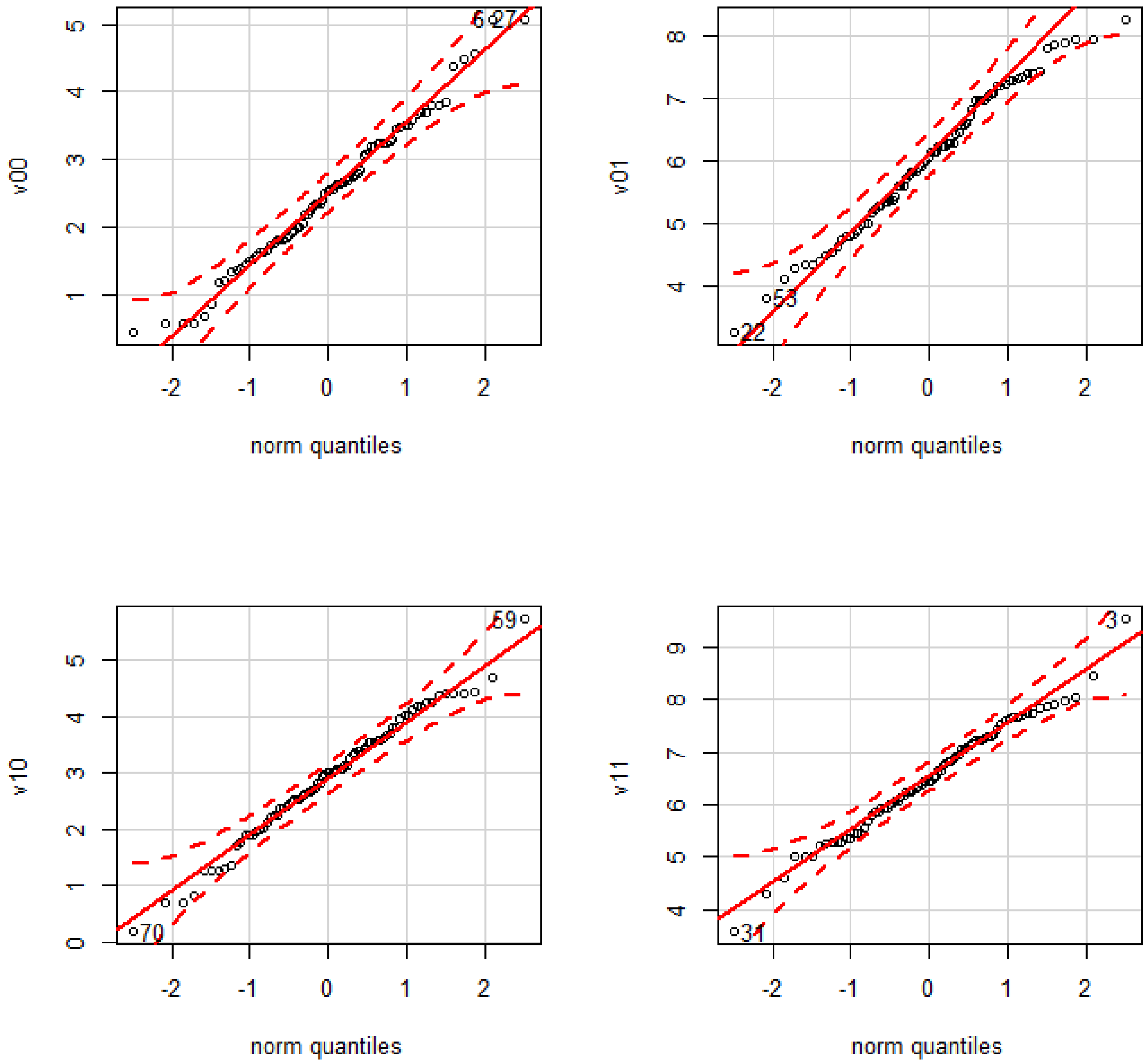


Figure 125. Q-Q plots for visual inspection of distribution characteristics.

Appendix C10 Symmetric beanplots for direct visual comparison between experimental conditions

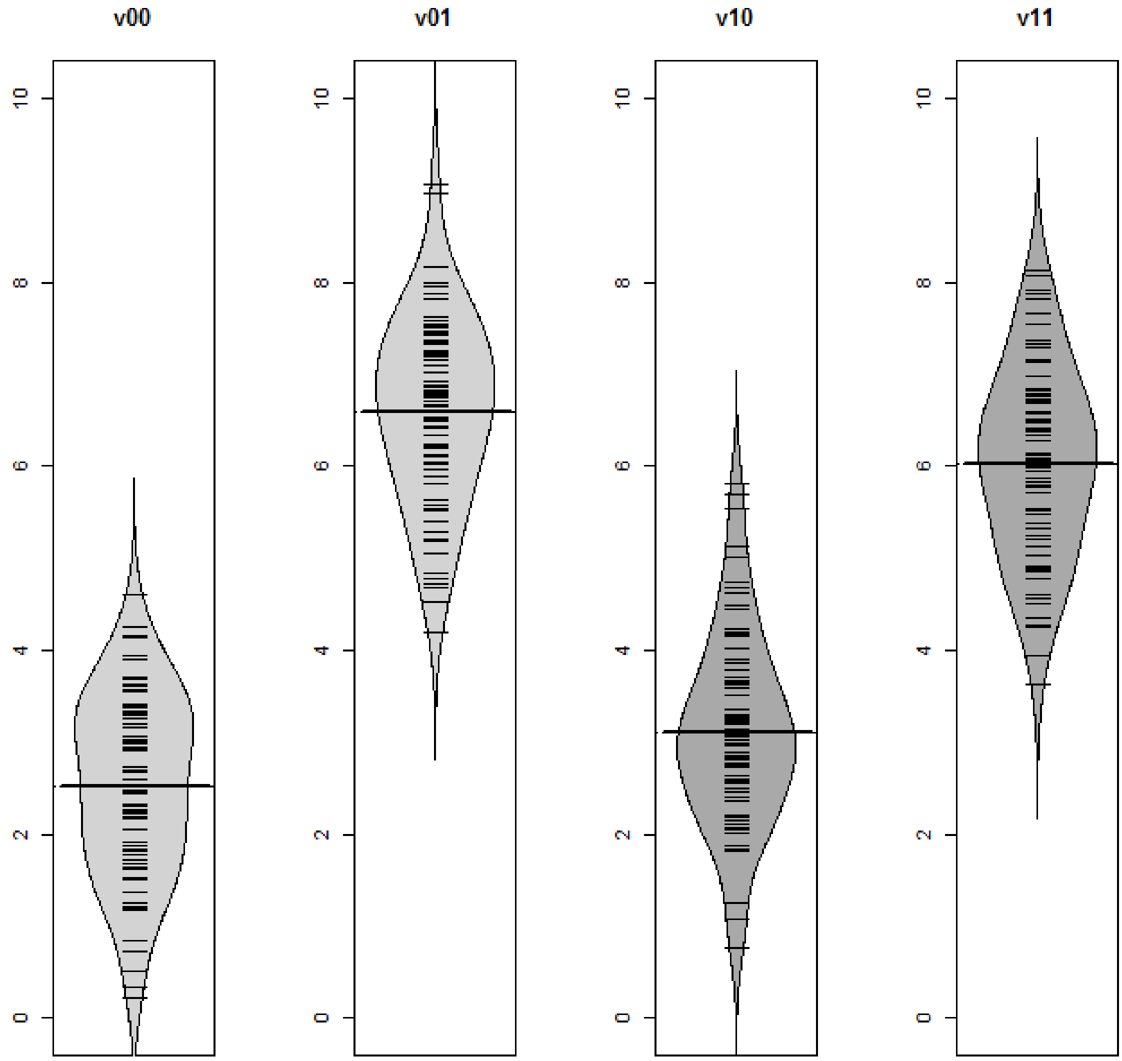


Figure 126. Symmetric beanplots for visual inspection of distribution characteristics.

Appendix C11 Descriptive statistics and various normality tests

Table 55

Descriptive statistics and various normality tests.

$`Descriptive Statistics`

	n	Mean	Std.Dev	Median	Min	Max	25th	75th	Skew	Kurtosis
v00	80	2.528	0.995	2.544	0.224	4.598	1.768	3.314	-0.229	-0.720
v10	80	3.100	1.060	3.043	0.772	5.810	2.448	3.684	0.323	0.060
v01	80	6.590	1.020	6.719	4.186	9.058	5.969	7.337	-0.130	-0.335
v11	80	6.030	1.030	6.058	3.626	8.124	5.237	6.711	-0.040	-0.617

$`Shapiro-Wilk's Normality Test`

	Variable	Statistic	p-value	Normality
1	v00	0.9805	0.2613	YES
2	v10	0.9815	0.3022	YES
3	v01	0.9883	0.6877	YES
4	v11	0.9889	0.7249	YES

$`Cramer-von Mises's Normality Test`

	Variable	Statistic	p-value	Normality
1	v00	0.0955	0.1273	YES
2	v10	0.0735	0.2480	YES
3	v01	0.0512	0.4902	YES
4	v11	0.0321	0.8138	YES

Appendix C12 χ2 Q-Q plot (Mahalanobis Distance)

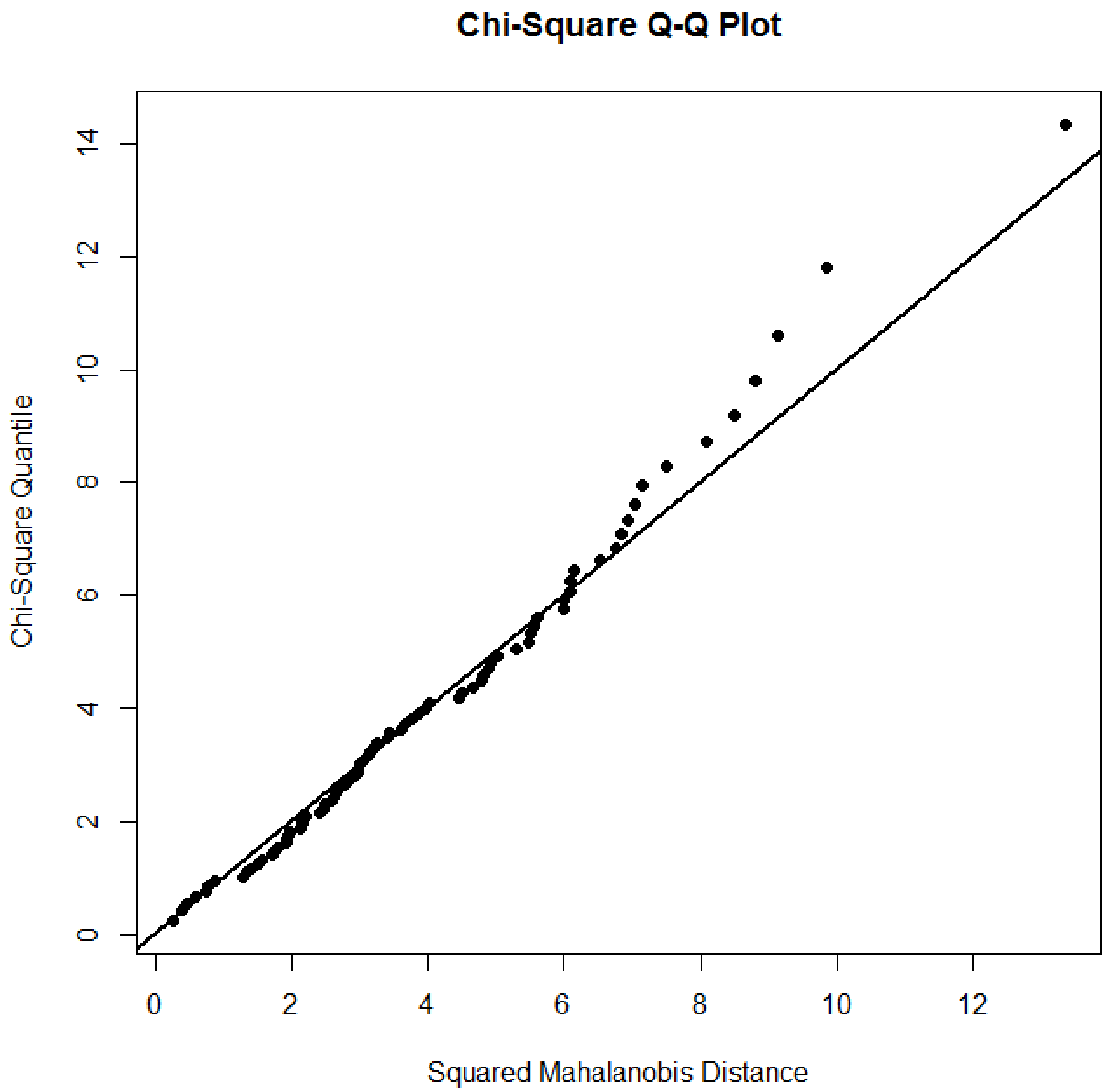


Figure 127. χ2 Q-Q plot (Mahalanobis Distance, D^2).

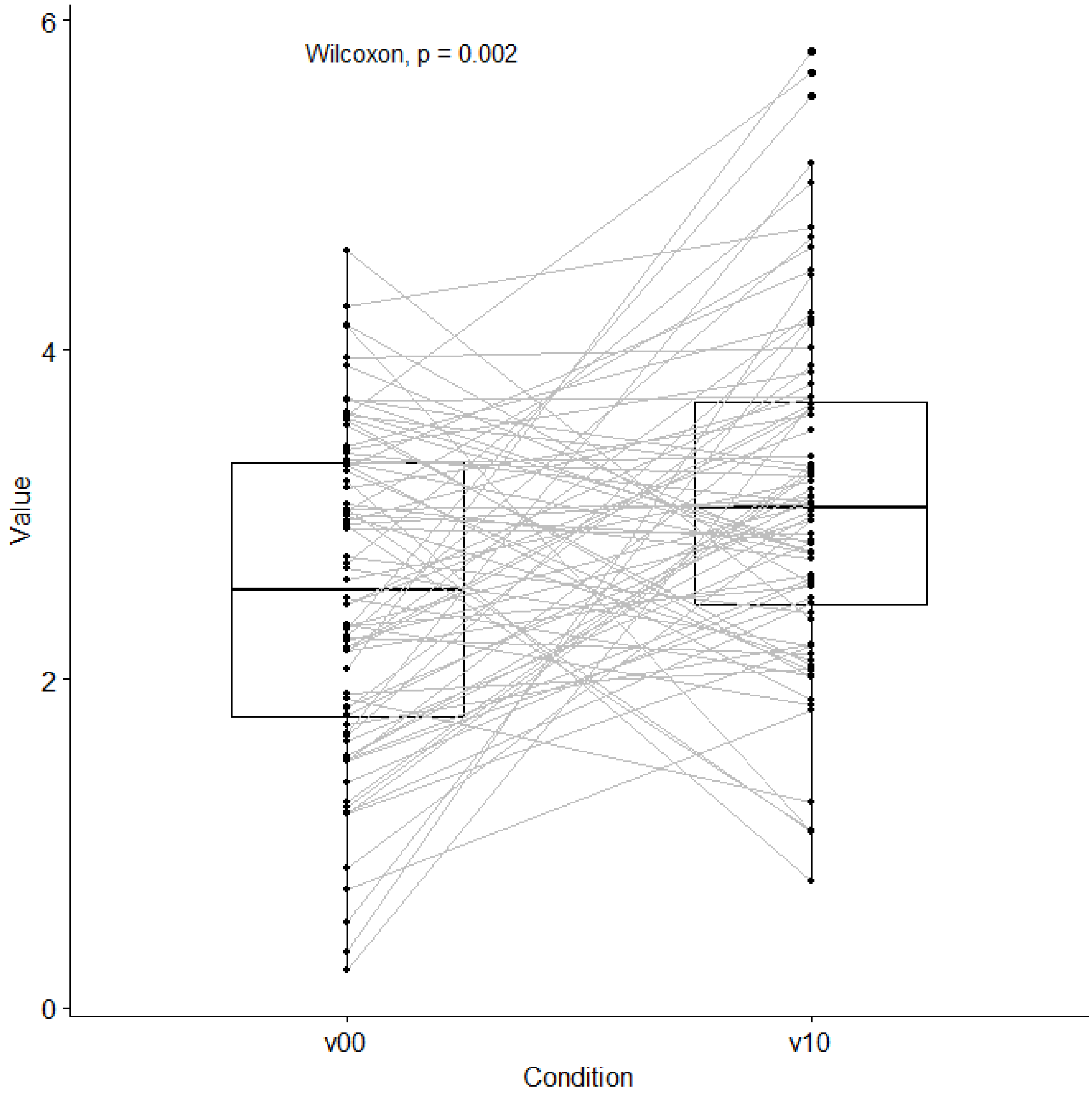
Note: Q-Q plot based on Royston's Multivariate Normality Test (see next page).

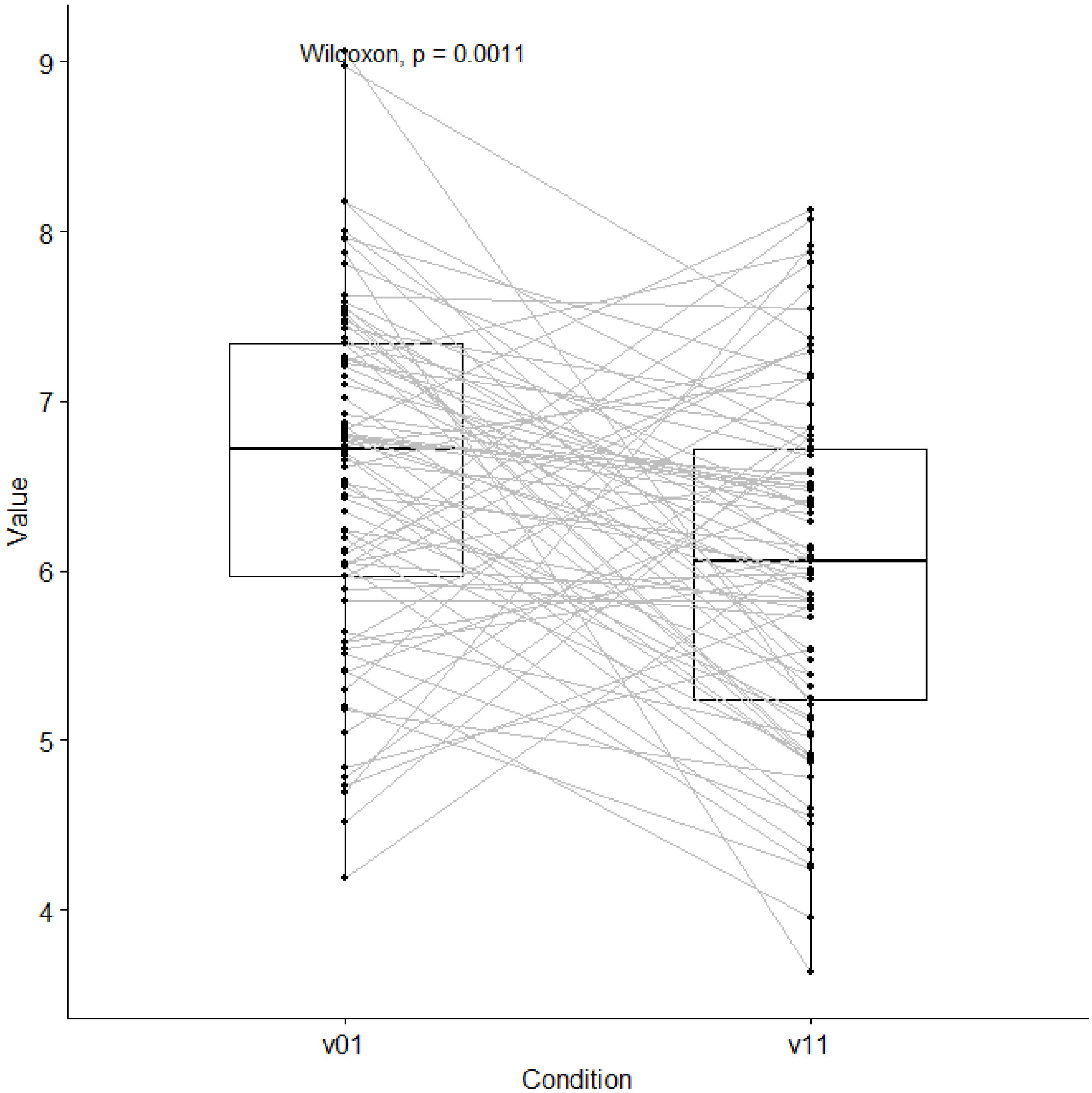
Table 56

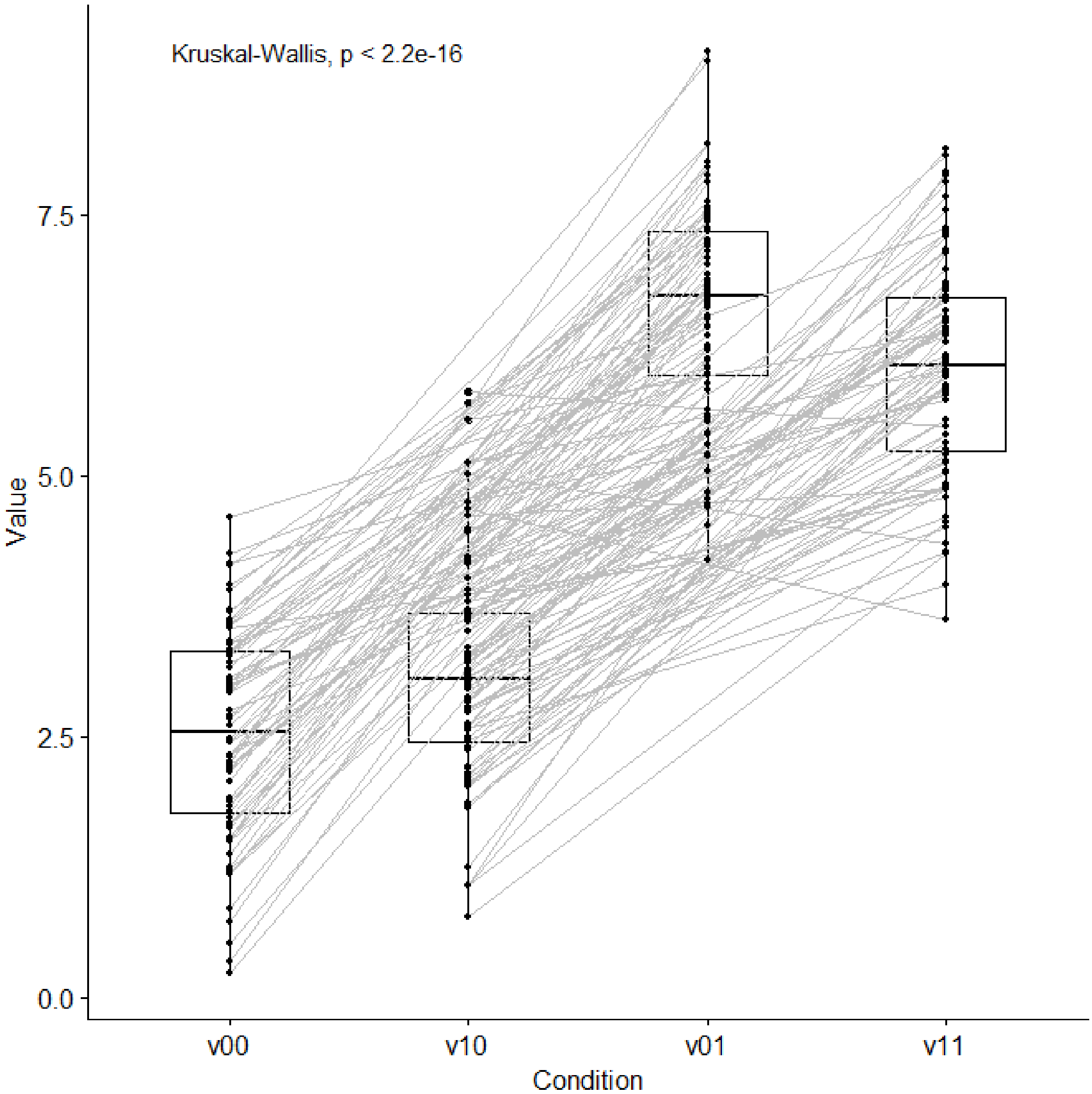
Royston's multivariate normality test.

```
  Royston's Multivariate Normality Test
---------------------------------------------
  data : dataexp3

  H       : 2.361587
  p-value : 0.6695777

  Result  : Data are multivariate normal.
---------------------------------------------
```

Appendix C13 Connected boxplots (with Wilcoxon test)




Wilcoxon, p = 0.0011
9
8
7
6
5
4
Value
v01
v11
Condition



Kruskal-Wallis, p < 2.2e-16
Value
7.5
5.0
2.5
0.0
v00
v10
v01
v11
Condition

Appendix C14 Correlational analysis

1st pair

```
        Pearson's product-moment correlation

data:  v00 and v10
t = 1.7026, df = 80, p-value = 0.09253
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.03128247  0.38824652
sample estimates:
      cor
0.1869941
```

Table 57

Numerical summary for all parameters associated with experimental condition V_{10} and V_{01} and their corresponding 95% posterior high density credible intervals.

Measures

	mean	sd	HDIlo	HDIup	%<comp	%>comp
rho	-0.080	0.114	-0.301	0.143	0.761	0.239
mu[1]	2.531	0.115	2.306	2.757	0.000	1.000
mu[2]	3.088	0.121	2.853	3.328	0.000	1.000
sigma[1]	0.999	0.085	0.836	1.167	0.000	1.000
sigma[2]	1.052	0.093	0.876	1.236	0.000	1.000
nu	46.710	31.655	5.671	109.173	0.000	1.000
xy_pred[1]	2.526	1.042	0.460	4.554	0.009	0.991
xy_pred[2]	3.087	1.103	0.882	5.254	0.004	0.996

Note. 'HDIlo' and 'HDIup' are the limits of a 95% HDI credible interval.

'%<comp' and '%>comp' are the probabilities of the respective parameter being smaller or larger than 0.

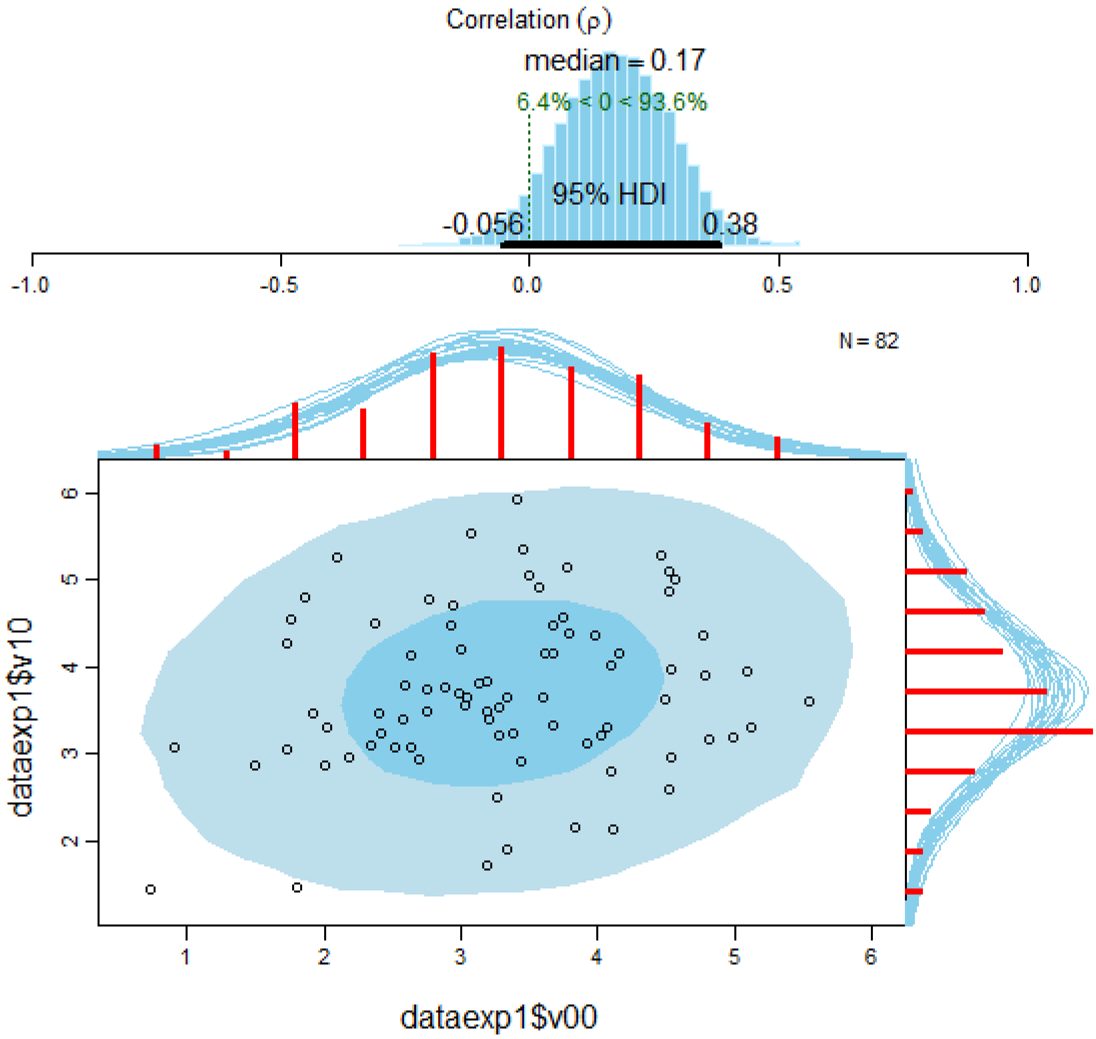
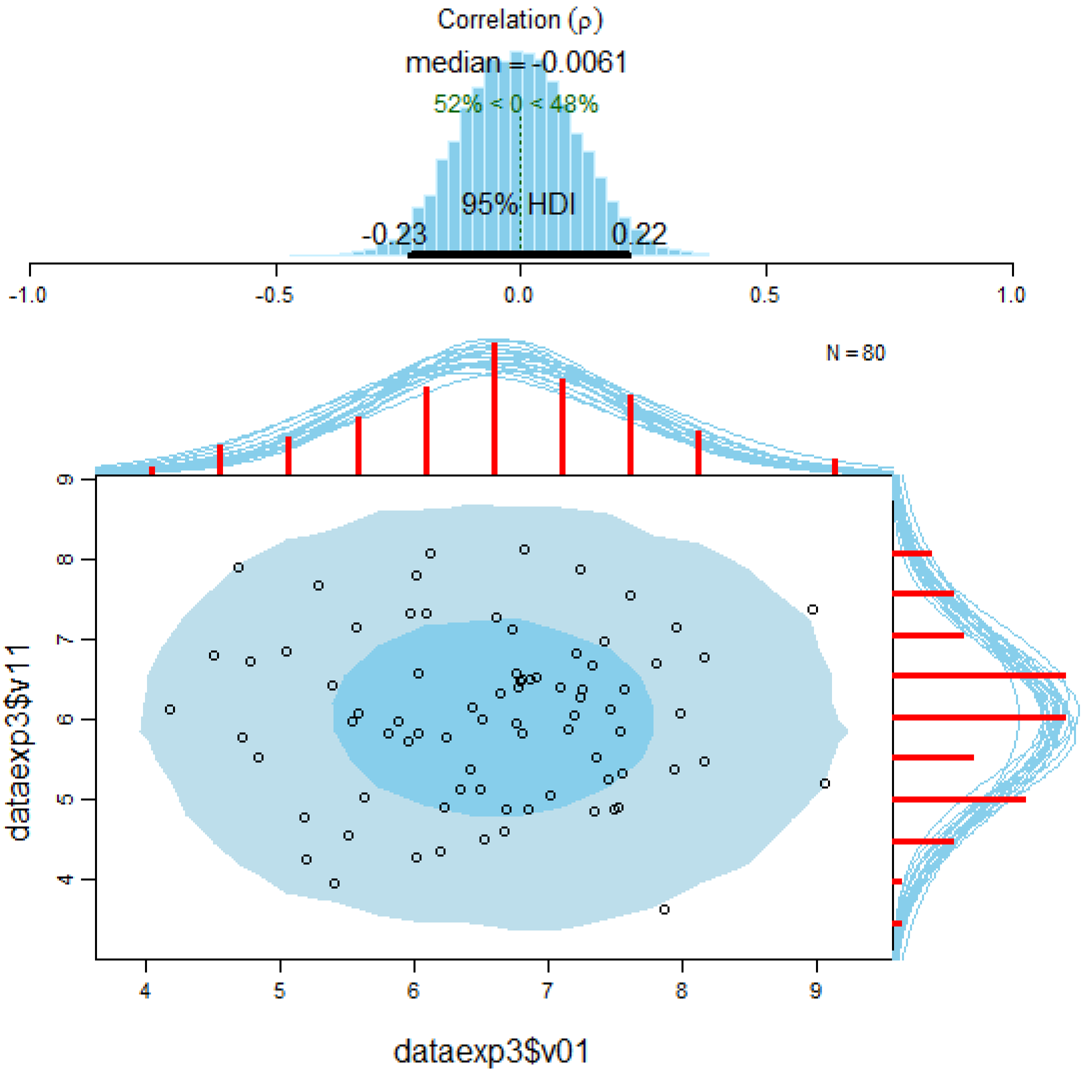


Figure 128. Visualisation of the results of the Bayesian correlational analysis for experimental condition V_{00} and V_{01} with associated posterior high density credible intervals and marginal posterior predictive plots.

2nd pair

```
       Pearson's product-moment correlation


data:  v01 and v11
t = -0.089628, df = 78, p-value = 0.9288
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.2293534  0.2100373
sample estimates:
       cor
-0.0101479
```

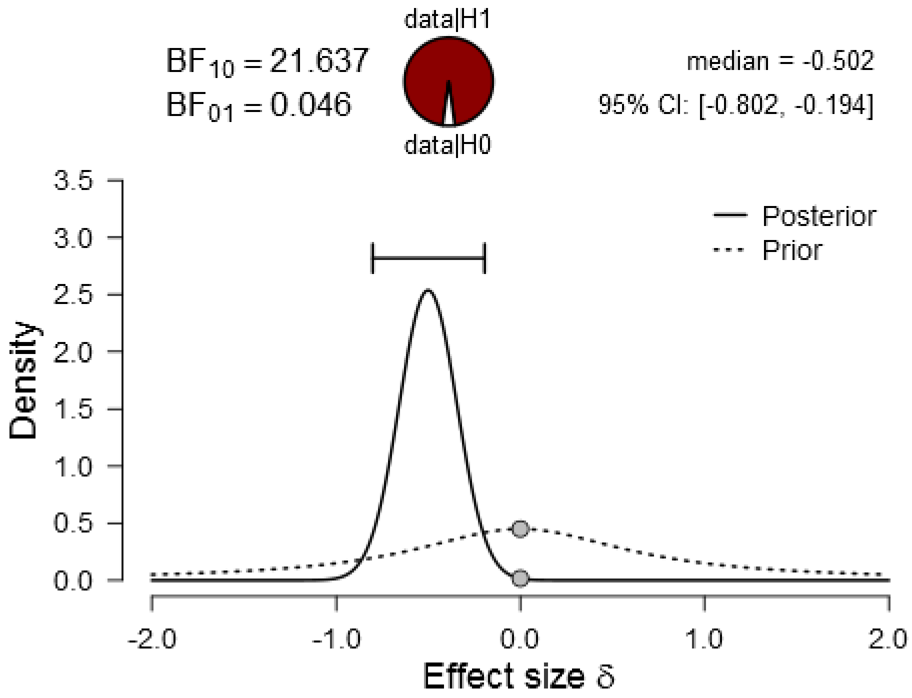
```
  Measures
              mean     sd  HDIlo   HDIup %<comp %>comp
rho         -0.006  0.115 -0.234   0.215  0.521  0.479
mu[1]        6.599  0.117  6.376   6.832  0.000  1.000
mu[2]        6.029  0.118  5.798   6.262  0.000  1.000
sigma[1]     1.016  0.088  0.850   1.192  0.000  1.000
sigma[2]     1.030  0.089  0.863   1.208  0.000  1.000
nu          46.614 31.849  5.444 109.464  0.000  1.000
xy_pred[1]   6.601  1.068  4.503   8.721  0.000  1.000
xy_pred[2]   6.032  1.079  3.910   8.182  0.000  1.000
```


Correlation (ρ)
median = -0.0061
52% < 0 < 48%
95% HDI
-0.23
0.22
-1.0
-0.5
0.0
0.5
1.0
N = 80
dataexp3$v11
dataexp3$v01

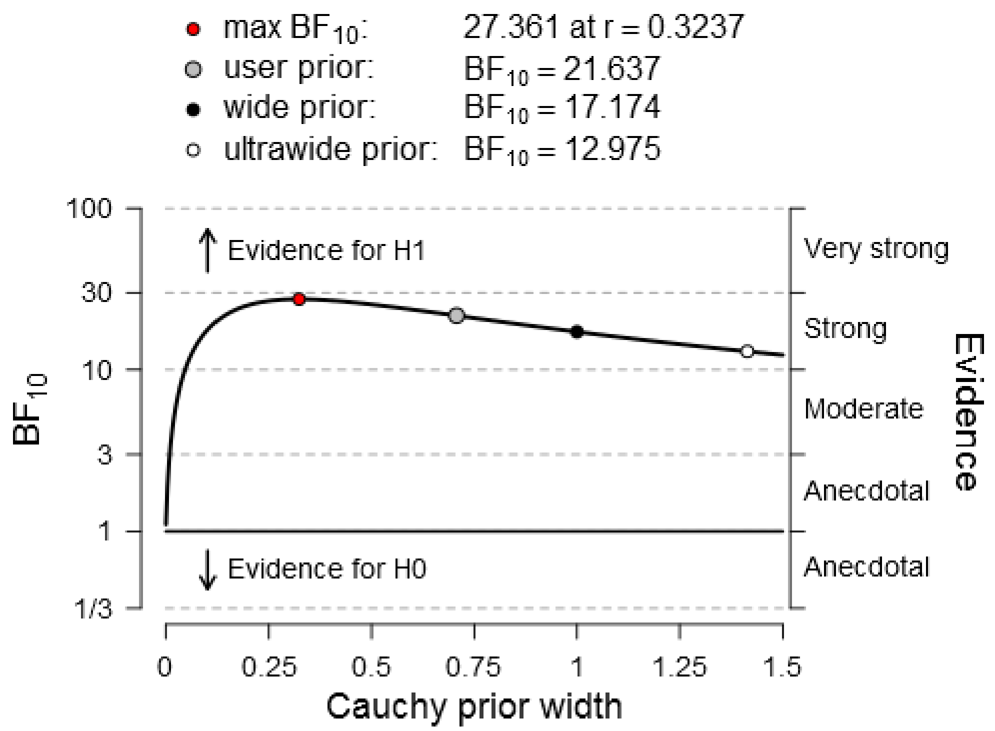
Appendix C15 Inferential Plots for Bayes Factor analysis

v00 - v10

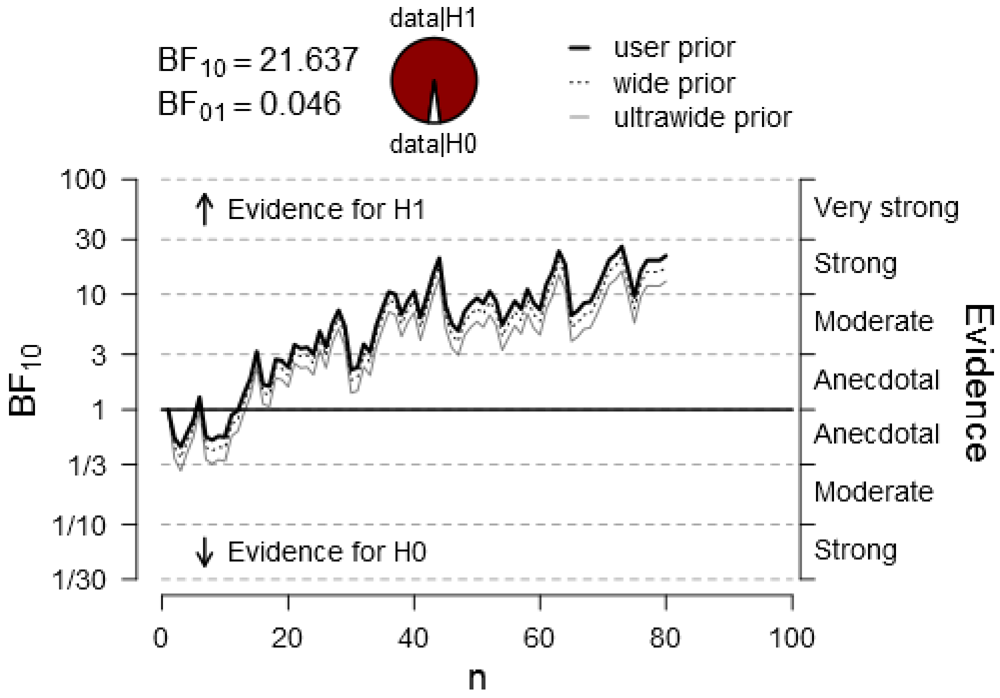
Prior and Posterior



Bayes Factor Robustness Check

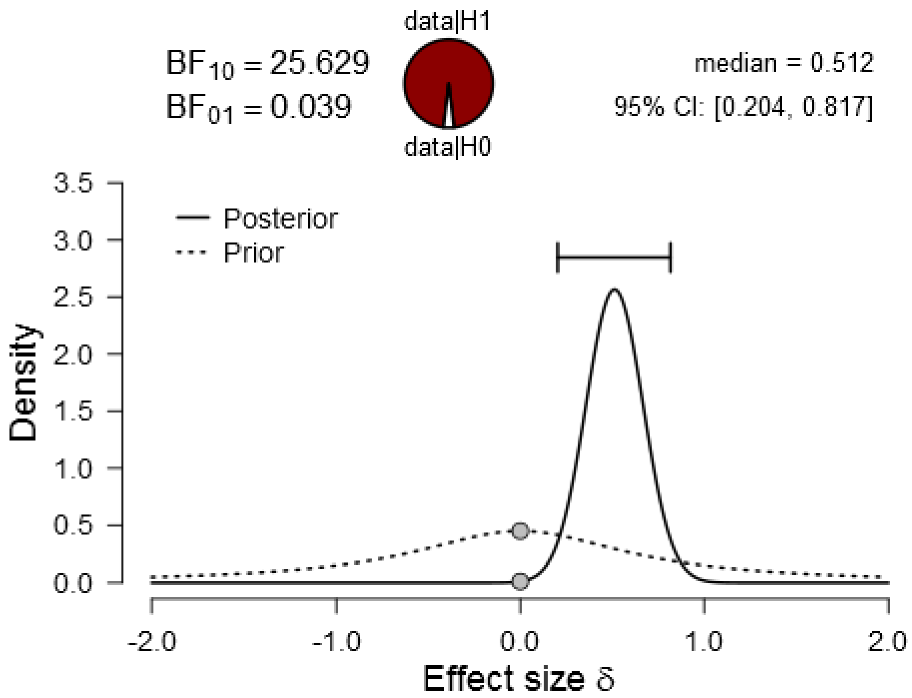


Sequential Analysis

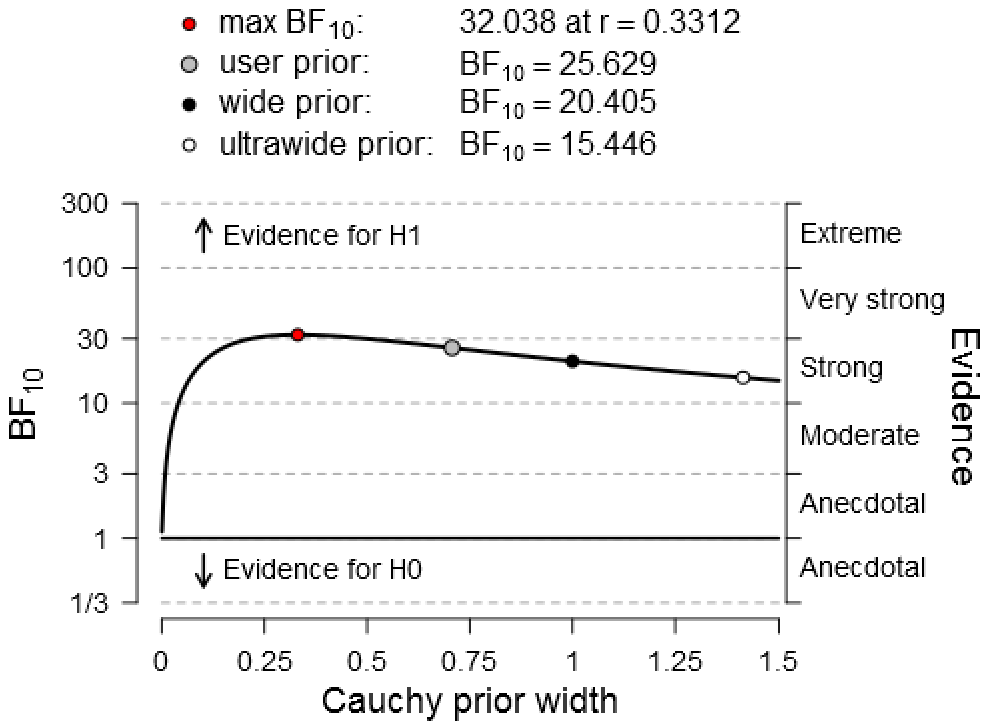


v01 - v11

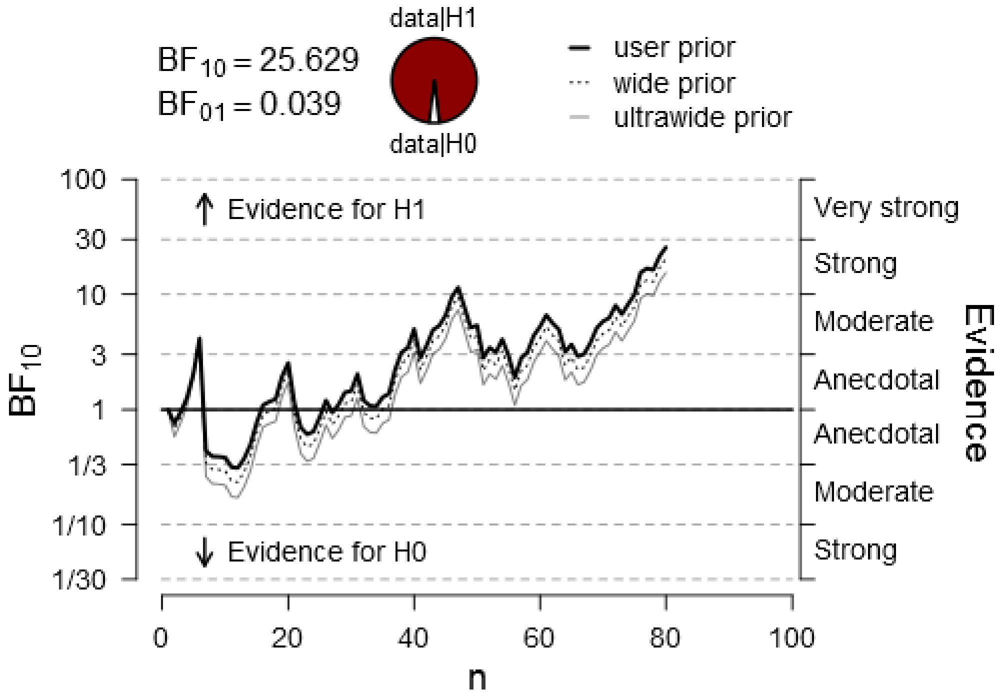
Prior and Posterior



Bayes Factor Robustness Check



Sequential Analysis



Appendix D Experiment 3

Appendix D1 Parametrisation of auditory stimuli

Table 58

Amplitude statistics for stimulus-0.6.wav.

Parameter	Left channel	Right channel
Peak Amplitude:	-11.54 dB	-11.60 dB
True Peak Amplitude:	-11.54 dBTP	-11.60 dBTP
Maximum Sample Value:	8674.67	8616.15
Minimum Sample Value:	-8662.86	-8612.15
Total RMS Amplitude:	-15.65 dB	-15.70 dB
Maximum RMS Amplitude:	-13.48 dB	-13.54 dB
Minimum RMS Amplitude:	-23.79 dB	-23.84 dB
Average RMS Amplitude:	-16.37 dB	-16.43 dB
DC Offset:	-0.01 %	-0.01 %
Measured Bit Depth:	24	24
Dynamic Range:	10.30 dB	10.30 dB
Dynamic Range Used:	10.20 dB	10.25 dB
Loudness (Legacy):	-13.88 dB	-13.93 dB
Perceived Loudness (Legacy):	-12.88 dB	-12.93 dB

Note. Statistics were computed by utilising Adobe© Audition CC 2017 which is part of the Adobe Creative Suite (Adobe Systems Incorporated) and are only indicative. The original pure tones are best replicated in PsychoPy (J. W. Peirce, 2007, 2008) using the parametrisation “0.6” and “0.8” for the loudness parameters, respectively.

Table 59

Amplitude statistics for stimulus-0.8.wav.

Parameter	**Left channel**	**Right channel**
Peak Amplitude:	-0.96 dB	-1.13 dB
True Peak Amplitude:	-0.96 dBTP	-1.13 dBTP
Maximum Sample Value:	29245.00	28706.16
Minimum Sample Value:	-29334.32	-28782.39
Total RMS Amplitude:	-6.25 dB	-6.41 dB
Maximum RMS Amplitude:	-4.05 dB	-4.22 dB
Minimum RMS Amplitude:	-12.96 dB	-13.12 dB
Average RMS Amplitude:	-6.90 dB	-7.06 dB
DC Offset:	0.08 %	0.08 %
Measured Bit Depth:	24	24
Dynamic Range:	8.91 dB	8.91 dB
Dynamic Range Used:	8.85 dB	8.90 dB
Loudness (Legacy):	-4.43 dB	-4.62 dB
Perceived Loudness (Legacy):	-3.58 dB	-3.73 dB

Appendix D2 Electronic supplementary materials: Auditory stimuli

Auditory stimuli can be downloaded from the following URLs:

http://irrational-decisions.com/phd-thesis/auditory-stimuli/stimulus-0.6.wav

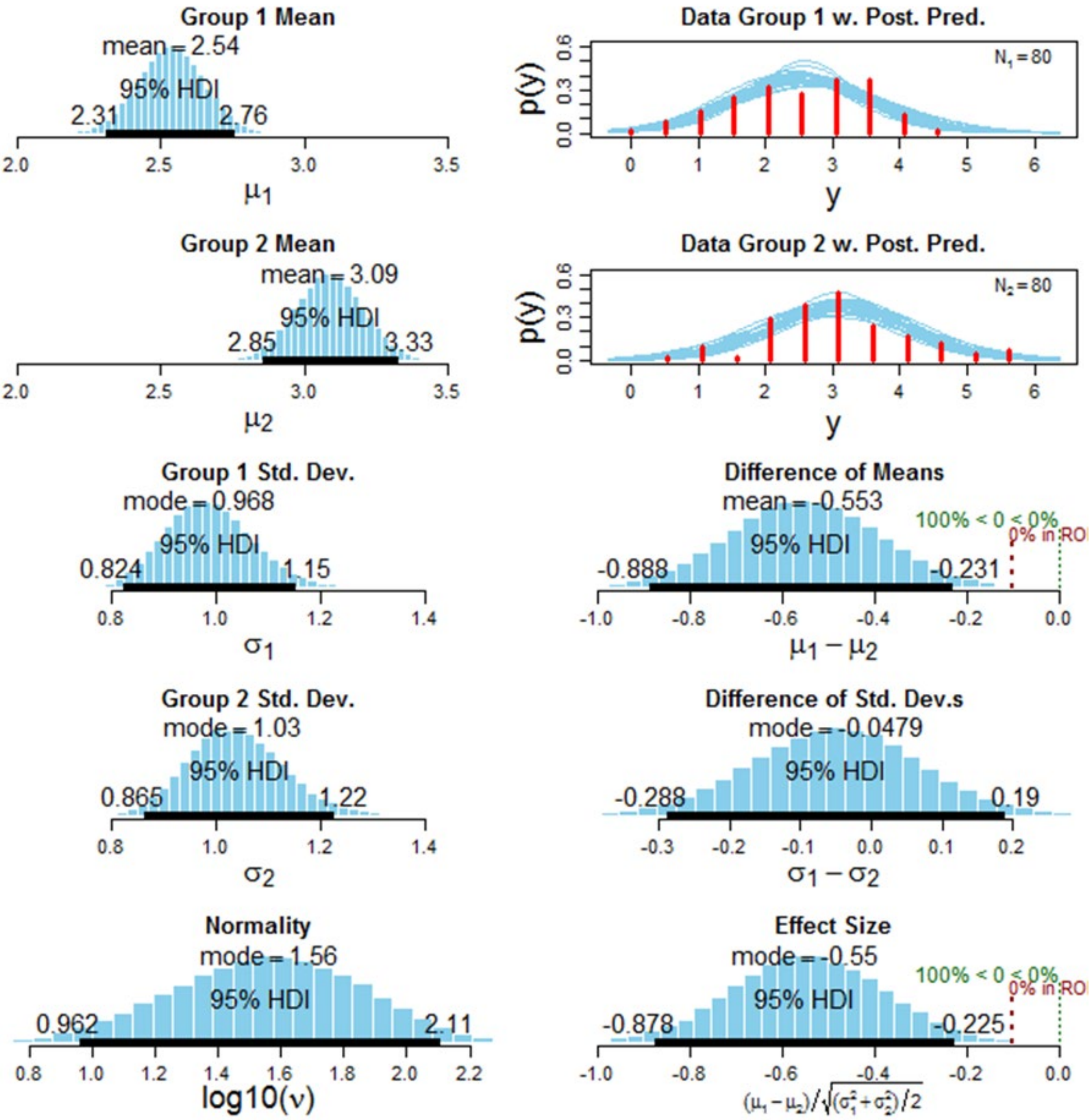
http://irrational-decisions.com/phd-thesis/auditory-stimuli/stimulus-0.8.wav

The original pure tones are best replicated in PsychoPy (J. W. Peirce, 2007, 2008) using the parametrisation “0.6” and “0.8” for the loudness parameters, respectively.

PsychoPy parametrisation

```
sound_1 = sound.Sound('A', secs=-1)

sound_1.setVolume(0.6)

sound_2 = sound.Sound('A', secs=-1)

sound_2.setVolume(0.8)
```

Appendix D3 Bayesian parameter estimation



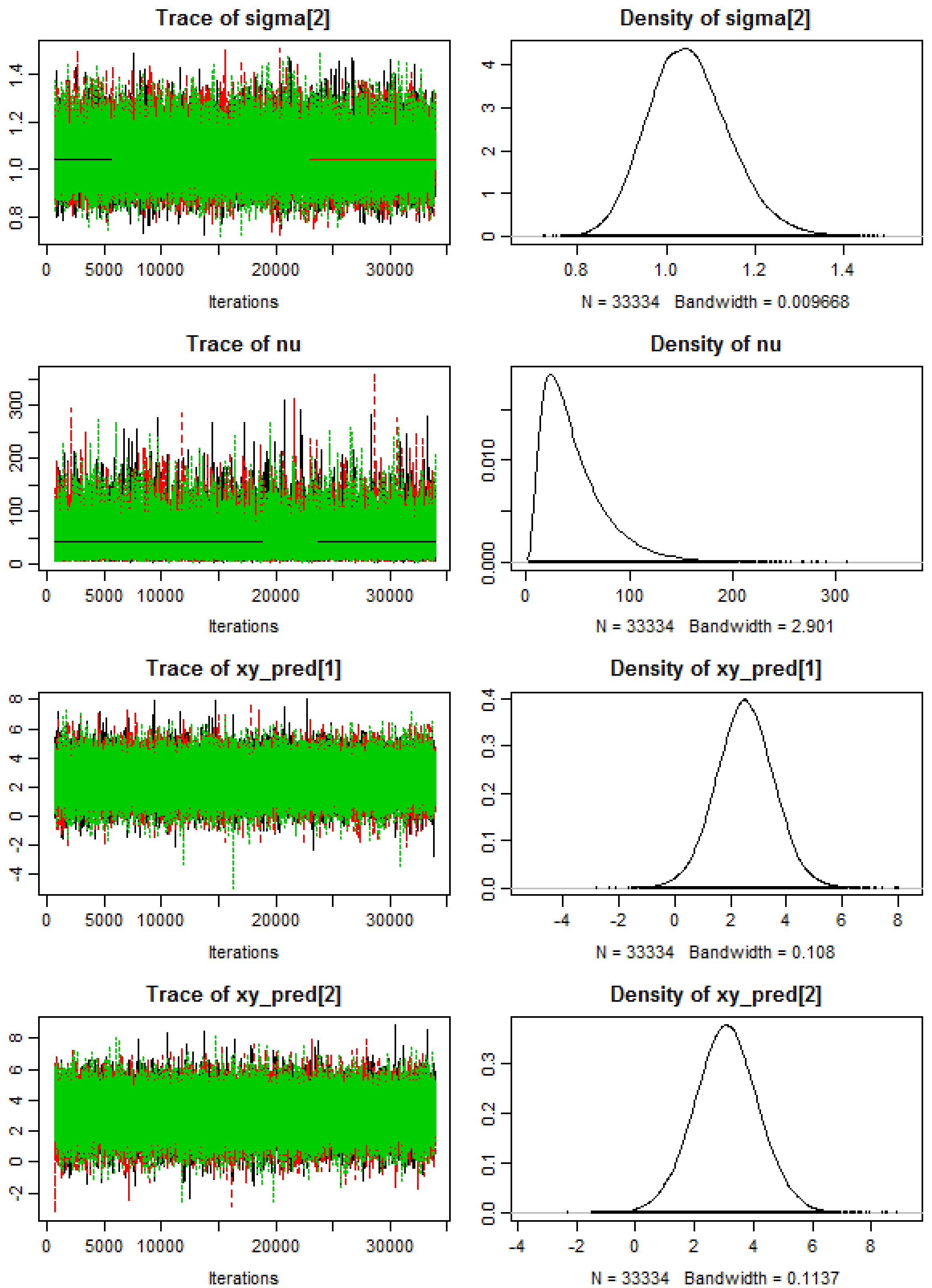
```
             mean  median    mode HDI%  HDIlo   HDIup compVal %>compVa
l
mu1        2.5355  2.5359  2.5348   95  2.311   2.757
mu2        3.0886  3.0878  3.0870   95  2.855   3.329
muDiff    -0.5531 -0.5531 -0.5579   95 -0.888  -0.231       0      0.0
4
sigma1     0.9884  0.9834  0.9680   95  0.824   1.154
sigma2     1.0392  1.0346  1.0308   95  0.865   1.225
sigmaDiff -0.0508 -0.0498 -0.0479   95 -0.288   0.190       0     33.8
6
nu        44.3790 36.0418 21.8557   95  5.149 106.906
log10nu    1.5492  1.5568  1.5611   95  0.962   2.106
effSz     -0.5462 -0.5465 -0.5503   95 -0.878  -0.225       0      0.0
4
```

```
          mean       sd  median  HDIlo   HDIup Rhat n.eff
mu1     2.5355  0.11433  2.5359 2.3106   2.757    1 58225
mu2     3.0886  0.12084  3.0878 2.8546   3.329    1 60056
nu     44.3790 31.21383 36.0418 5.1493 106.906    1 23284
sigma1  0.9884  0.08517  0.9834 0.8237   1.154    1 53227
sigma2  1.0392  0.09187  1.0346 0.8649   1.225    1 48718

'HDIlo' and 'HDIup' are the limits of a 95% HDI credible interval.
'Rhat' is the potential scale reduction factor (at convergence, Rhat=1
).
'n.eff' is a crude measure of effective sample size.
```

Appendix D4 Correlational analysis

Diagnostics for first pair

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
             mean     sd mcmc_se  n_eff Rhat
rho        -0.080  0.114   0.000  60094    1
mu[1]       2.531  0.115   0.000  59875    1
mu[2]       3.088  0.121   0.000  59789    1
sigma[1]    0.999  0.085   0.000  52540    1
sigma[2]    1.052  0.093   0.000  49827    1
nu         46.710 31.655   0.210  22849    1
xy_pred[1]  2.526  1.042   0.003  99942    1
xy_pred[2]  3.087  1.103   0.003 100343    1

mcmc_se: the estimated standard error of the MCMC approximation of the
mean.
n_eff: a crude measure of effective MCMC sample size.
Rhat: the potential scale reduction factor (at convergence, Rhat=1).

  Model parameters
rho: the correlation between dataexp3$v00 and dataexp3$v10
mu[1]: the mean of dataexp3$v00
sigma[1]: the scale of dataexp3$v00 , a consistent
  estimate of SD when nu is large.
mu[2]: the mean of dataexp3$v10
sigma[2]: the scale of dataexp3$v10
nu: the degrees-of-freedom for the bivariate t distribution
xy_pred[1]: the posterior predictive distribution of dataexp3$v00
xy_pred[2]: the posterior predictive distribution of dataexp3$v10
```

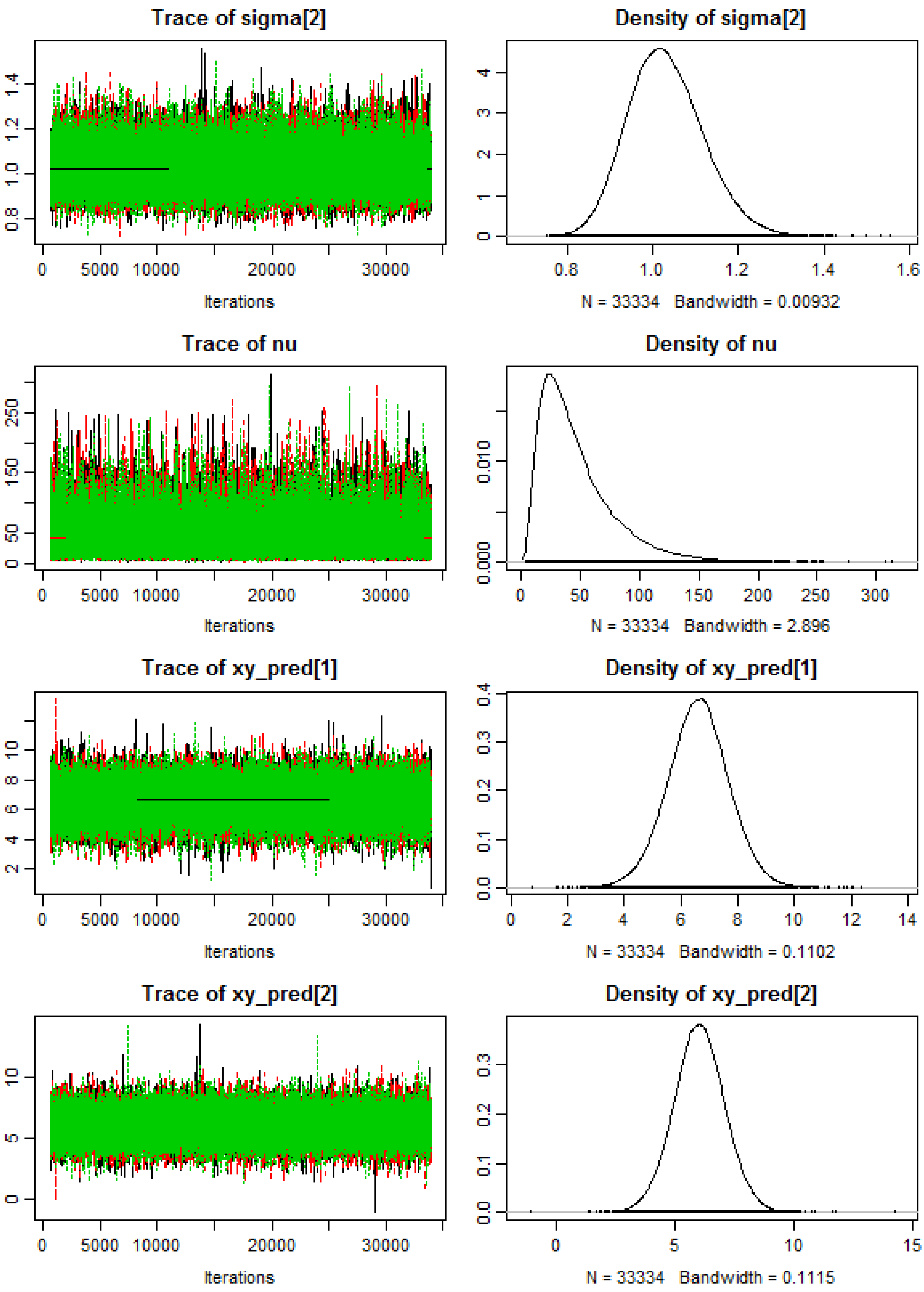

Trace of sigma[2]
Iterations
Density of sigma[2]
N = 33334 Bandwidth = 0.009668
Trace of nu
Iterations
Density of nu
N = 33334 Bandwidth = 2.901
Trace of xy_pred[1]
Iterations
Density of xy_pred[1]
N = 33334 Bandwidth = 0.108
Trace of xy_pred[2]
Iterations
Density of xy_pred[2]
N = 33334 Bandwidth = 0.1137

Quantiles of Bayesian correlation analysis for first pair

```
  Quantiles
            q2.5%   q25% median   q75%  q97.5%
rho        -0.299 -0.158 -0.081 -0.004   0.145
mu[1]       2.303  2.454  2.531  2.608   2.755
mu[2]       2.851  3.008  3.088  3.169   3.326
sigma[1]    0.847  0.940  0.994  1.053   1.181
sigma[2]    0.886  0.988  1.046  1.110   1.249
nu         10.172 24.065 38.521 60.742 128.927
xy_pred[1]  0.476  1.843  2.524  3.208   4.579
xy_pred[2]  0.908  2.369  3.085  3.806   5.285
```

Diagnostics for second pair

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
              mean     sd mcmc_se  n_eff Rhat
rho         -0.006  0.115   0.000  62078    1
mu[1]        6.599  0.117   0.000  60842    1
mu[2]        6.029  0.118   0.000  61415    1
sigma[1]     1.016  0.088   0.000  49569    1
sigma[2]     1.030  0.089   0.000  52429    1
nu          46.614 31.849   0.207  23975    1
xy_pred[1]   6.601  1.068   0.003  99166    1
xy_pred[2]   6.032  1.079   0.003 100010    1

mcmc_se: the estimated standard error of the MCMC approximation of the
mean.
n_eff: a crude measure of effective MCMC sample size.
Rhat: the potential scale reduction factor (at convergence, Rhat=1).

  Model parameters
rho: the correlation between dataexp3$v01 and dataexp3$v11
mu[1]: the mean of dataexp3$v01
sigma[1]: the scale of dataexp3$v01 , a consistent
  estimate of SD when nu is large.
mu[2]: the mean of dataexp3$v11
sigma[2]: the scale of dataexp3$v11
nu: the degrees-of-freedom for the bivariate t distribution
xy_pred[1]: the posterior predictive distribution of dataexp3$v01
xy_pred[2]: the posterior predictive distribution of dataexp3$v11
```


Trace of sigma[2]
Iterations
Density of sigma[2]
N = 33334   Bandwidth = 0.00932
Trace of nu
Iterations
Density of nu
N = 33334   Bandwidth = 2.896
Trace of xy_pred[1]
Iterations
Density of xy_pred[1]
N = 33334   Bandwidth = 0.1102
Trace of xy_pred[2]
Iterations
Density of xy_pred[2]
N = 33334   Bandwidth = 0.1115

Quantiles of Bayesian correlation analysis for second pair

Quantiles

	q2.5%	q25%	median	q75%	q97.5%
rho	-0.231	-0.084	-0.006	0.072	0.219
mu[1]	6.370	6.521	6.599	6.678	6.827
mu[2]	5.796	5.950	6.029	6.108	6.260
sigma[1]	0.859	0.955	1.011	1.072	1.203
sigma[2]	0.871	0.969	1.025	1.086	1.218
nu	10.016	23.886	38.393	60.502	129.729
xy_pred[1]	4.471	5.908	6.607	7.301	8.691
xy_pred[2]	3.895	5.328	6.028	6.738	8.16

Appendix E Experiment 4

Appendix E1 Markov chain Monte Carlo simulations

Model comparison via Bayes Factor (Bayesian confirmation theory) as described in the antecedent chapter is thus not the only viable Bayesian alternative to classical frequentist NHST. Bayesian parameter estimation and Bayes Factor analysis differ in significant ways: Compared to Bayes Factor analysis, the Bayesian parameter estimation approach provides much richer information because it results in a posterior probability distribution on all parameters (Bayes Factor analysis does not). Model comparison and Bayesian parameter estimation are both committed to Bayes' theorem as the axiomatic foundation for probabilistic inductive inferences. However, the questions they address are fundamentally different (Steel, 2007). Whereas model comparison is concerned with the evaluation (i.e., confirmation/rejection) of hypotheses, Bayesian parameter estimation is primarily concerned with the computation of posterior probability distributions for the parameters of interest. However, the Bayesian parameter estimation approach can also be utilised to test specific research hypotheses. In the model comparison approach, the decision (accept vs. reject) is based on a predefined arbitrary threshold (i.e., the strength of the Bayes Factor). In the parameter estimation approach, on the other hand, the inferential decision is based on the specification of a threshold for the parameter under investigation (viz. a "posterior high density interval" in combination with a "region of practical equivalence"). The parameter estimation approach and its associated methods for hypothesis testing will be described in more detail in the following subsections.

In sum, both Bayesian methods base the decision rule on the posterior distribution. However, given that they focus on different facets of the posterior distribution the resulting inferences do not necessarily have to coincide (Kruschke, 2014). Furthermore, both inferential approaches are based on the notion of credence (a subjective “Bayesian” probability describing the level of confidence or belief). Given that subjectivity involves the epistemological idiosyncrasies and propensities of a human cogniser, credence must be regarded as a psychological property.

In the Bayesian framework, beliefs are always provisional (as opposed to the positivist notion of deductive *absolute* certainty). In the scientific sense, this means a tentative acceptance of a theory or hypothesis combined with an explicit sense of fallibilism[245] (a willingness to admit that the theory/hypothesis might in principle be wrong). The explicit willingness to revise or even negate (oftentimes cherished) ideas in the light of new evidence is a crucial aspect of genuine scientific thinking. Fallibilism is thus a general scientific attitude towards knowledge (an epistemic virtue). The writings of the influential philosopher of science, Karl Popper, partially agree with this epistemological stance. His “conjecture and refutation model” of “growth of scientific knowledge” (1962) is based on the notion that open-mindedness and intellectual humility are the primary characteristic that render science a rational enterprise (see also C. S. Peirce, 1955).

Appendix E2 Theoretical background of Bayesian inference

Bayesian inference has gained significantly in importance since its development in the late 1990s, especially in the field of evolutionary biology (e.g., phylogenetic inference), for a review see Huelsenbeck (2001). This continuing trend is visualised in Figure 129. In general terms, Bayesian inference employs Bayes’ theorem in order to condition

[245] Fallabilism asserts that a given propositions concerning empirical knowledge can be accepted even though it cannot be conclusively proven with absolute certainty. The term is etymologically derived from the Latin: *fallibilis*, meaning "liable to err" (G Gigerenzer, 1998).

inferences about the numerical value of some parameter θ on the observed empirical data (Alfaro, Zoller, & Lutzoni, 2003). The primary focus of Bayesian inference lies on the posterior distribution or posterior probability, i.e., the probability of a given hypothesis conditional on the empirical data.

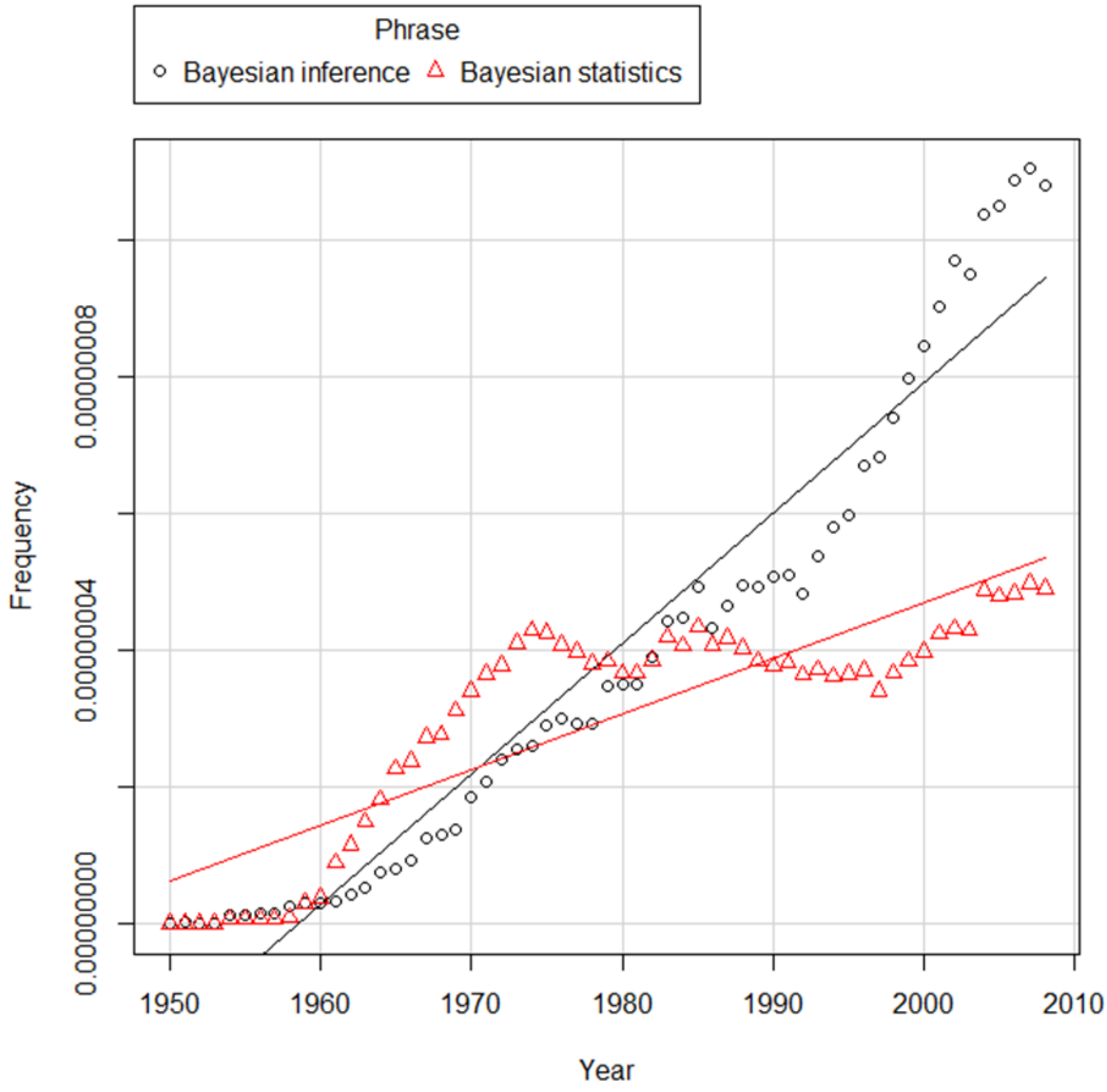


Figure 129. Graphic depicting the frequency of the terms “Bayesian inference” and Bayesian statistics” through time (with least square regression lines).

Statistics are based on various text corpora (data extracted from Google Ngram). The visualisation was created with the R package ngramr[246] and the data visualisation package ggplot2 (Ggplot2 Development Team, 2012; Wickham, 2009, 2011).

```
#ngramr manual as pdf:
#http://ftp.cs.pu.edu.tw/network/CRAN/web/packages/ngramr/ngramr.pdf

install.packages("ggplot2")
library(ggplot2)
#ggplot2 Development Team. (2012). Ggplot2-0.9.0. Production, (ii), 1–41.
#Wickham, H. (2011). ggplot2. Wiley Interdisciplinary Reviews: Computational Statistics,
3(2), 180–185. https://doi.org/10.1002/wics.147
#Wickham, H. (2009). Ggplot2. Elegant Graphics for Data Analysis.
https://doi.org/10.1007/978-0-387-98141-3

#install R developer tools
install.packages("devtools")
#get ngramr package from github repository: https://github.com/
install_github("ngramr", "seancarmody")
require(ngramr)
require(ggplot2)
require(devtools)

freq <- ngram(c("p-value", "bayes factor"), year_start = 1950)
head(freq)
summary(freq)
names(freq)
```

[246] The manual for `ngramr` is available under http://ftp.cs.pu.edu.tw/network/CRAN/web/packages/ngramr/ngramr.pdf

```
write.table(freq, "ngram_bayes.txt", sep = "\t")


ng  <- ngram(c("Bayesian inference", "Bayesian statistics"), year_start = 1950)

ggplot(ng, aes(x = Year, y = Frequency, colour = Phrase)) +

  geom_line() + geom_line(linetype = "dashed") +

  geom_point() + theme(

    panel.grid.major = element_blank(),

    panel.grid.minor = element_blank(),

    panel.background = element_blank(),

    axis.line = element_line(colour = "black")

  )


ng


#in R commander

scatterplot(

  Frequency ~ Year | Phrase,

  reg.line = FALSE,

  smooth = FALSE,

  spread = FALSE,

  boxplots = FALSE,

  span = 0.5,

  ellipse = FALSE,

  levels = c(.5, .9),

  by.groups = TRUE,

  data = ng

)

scatterplot(

  Year ~ Frequency | Phrase,

  reg.line = lm,
```

```
  smooth = FALSE,
  spread = FALSE,
  boxplots = FALSE,
  span = 0.5,
  ellipse = TRUE,
  levels = c(.5, .9),
  jitter = list(x = 1, y = 1),
  by.groups = TRUE,
  data = ng
)
```

Code 10. R code to download, save, and plot data from Google Ngram. Various R packages are required (devtools, ngramr, ggplot2).

While hypothesis testing plays a pivotal role in psychology and the biomedical sciences, it is ancillary in many other scientific disciplines (e.g., physics). Many disciplines that do not primarily rely on hypothesis testing focus on estimation and modelling. A common problem in statistical modelling is to estimate the values of parameter of a given probability distribution. Bayesian Parameter Estimation (BPE) methods provide a set of powerful and robust statistical tools to obtain these values. In other words, BPE can produce accurate approximations to the Bayesian posterior distributions of various parameters (θ, i.e., theta) of interest. That is, parameters are modelled as probability distributions. BPE utilises computationally expensive Markov chain Monte Carlo (MCMC) algorithms to achieve this goal. In contrast to NHST, BPE fixes the empirical data and instead assumes a range of credible values for θ. Moreover, BPE allows probabilities to represent credibility (i.e., subjective certainty/belief). Hence, an appropriate alternative nomenclature for BPE (and all other Bayesian methods) would be “statistical uncertainty modelling”.

In the experimental context at hand, we applied Bayesian parameter estimation methods to our empirical data in order to obtain accurate estimates of the parameter values of interest. Based on the *a priori* defined hypotheses, we were particularly interested in the posterior distribution of the means per condition, their standard deviation, and the difference between means. BPE provides informative posterior probability distribution for all parameters of interest.

In the subsequent subsection we will provide a brief introduction to Bayesian parameter estimation via Markov chain Monte Carlo methods. Next, we will describe the software packages and statistical methods we utilised for our analysis. The third section will describe the actual Bayesian analysis and the results. This section is subdivided as follows (according to the sequential steps of the analysis):

6. Definition of the descriptive model and specification of priors
7. MCMC computations of the posterior distributions
8. Diagnostics/assessment of MCMC convergence
9. Summary and interpretation of the resulting posterior distributions within the pertinent theoretical framework

The Bayesian inferential approach we employed provides rich information about the estimated distribution of several parameters of interest, i.e., it provides the distribution of the estimates of μ and σ of both conditions and the associated effect sizes. Specifically, the method provides the "relative credibility" of all possible differences between means, standard deviations (Kruschke, 2013). Inferential conclusions about null hypotheses can be drawn based on these credibility values. In contrast to conventional NHST, uninformative (and frequently misleading[247]) p values are redundant in the Bayesian framework. Moreover, the Bayesian parameter estimation approach enables the researcher to accept null hypotheses. NHST, on the other, only allows the researcher to reject such null hypotheses.

The critical reader might object why one would use complex Bayesian computations for the relatively simple within-group design at hand. One might argue that a more parsimonious analytic approach is preferable. Exactly this question has been articulated before in a paper entitled "Bayesian computation: a statistical revolution" which was published in the Philosophical Transactions of the Royal Society: "*Thus, if your primary question of interest can be simply expressed in a form amenable to a t test, say, there*

[247] For more detailed information on the frequent logically fallacious misinterpretations of p-values and related frequentist statistics see chapter xxx.

really is no need to try and apply the full Bayesian machinery to so simple a problem" (S. P. Brooks, 2003, p. 2694).

The answer is straightforward: "*Decisions based on Bayesian parameter estimation are better founded than those based on NHST, whether the decisions derived by the two methods agree or not. The conclusion is bold but simple: Bayesian parameter estimation supersedes the NHST t test*" (Kruschke, 2013, p. 573).

Bayesian parameter estimation is more informative than NHST[248] (independent of the complexity of the research question under investigation). Moreover, the conclusions drawn from Bayesian parameter estimates do not necessarily converge with those based on NHST. This has been empirically demonstrated beyond doubt by several independent researchers (Kruschke, 2013; Rouder et al., 2009).

The juridical metaphor used before in the context of α-error inflation (see section xxx) is also applicable in the context of Bayesian estimation. The principle of exoneration illustrates the underlying logic of Bayesian inference. When a judge has to decide which of two unaffiliated defendants is guilty of a crime, evidence that incriminates one suspect automatically exonerates the other defendant. This is complementary reallocation of probabilities according the third Aristotelian law of the excluded middle[249], the *tertium non datur* (lit. no third [possibility] is given) a.k.a. *principium tertii exclusi*. The third Aristotelian "law of thought" stipulates that any given proposition can either be true or false (there is no intermediate middle ground)[250]. It implies that either a proposition is true, or its negation is true (Kalsi, 1994). This

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248 It is also more informative than Bayes factor analysis.

249 Modern quantum physics challenges this logical postulate. We will discuss this fundamental law of thought in chapter xxx in the context of superposition and complementarity.

250 This foundational and usually unquestioned axiom has been challenged by quantum physics (Leibfried et al., 2005; C. Monroe, Meekhof, King, & Wineland, 1996; Schrödinger, 1935). The concepts "superposition" and "complementarity" are discussed in chapter xxx as they play a pivotal role in the quantum cognition paradigm.

principle is exemplified in a famous quote by factious consulting detective Sherlock Holmes who is renowned for his logical reasoning and often cited by Bayesians:

"*Once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth*." (Dolye, 1904)

"As in the situation of Holmesian deduction, this exoneration is not only intuitive, it is also what the exact mathematics of Bayesian inference prescribe" (Kruschke, 2014, p. 19). For an exposition of "Bayesian thought in early modern detective stories" see Kadane (2009). However, from an informal logic point of view this is a fallacious argument and its form is known as the *argumentam ad ignorantiam,* Latin for argument from ignorance where ignorance here means "a lack of contrary evidence," (cf. Walton, 1992). This class of arguments fails to acknowledge one's own epistemological limitations (i.e., the limits of one's own understanding). In cognitive and social psychology, being ignorant of one's own ignorance is known as the "Dunning-Kruger effect" (Dunning, 2011; Kruger & Dunning, 1999). Yet, in the context of Bayesian reasoning it has been pointed out that "viewed probabilistically, these versions of the argument from ignorance constitute a legitimate form of reasoning" (Oaksford & Hahn, 2004, p. 75). As a syllogism the argument can be represented in the following form (*modus ponens*):

Major premise:	There is currently no evidence that p is true.
Minor premise:	If p were true, there would be evidence.
∴ Conclusion:	Ergo, p is false.

This syllogism is logically valid. However, the following argument might appear believable from a semantic point of view, but it is logically invalid:

Major premise:	There is currently no evidence that p is true.
Minor premise:	If p were true, there would be no evidence.
∴ Conclusion:	Ergo, p is false.

Even though this argument might appear semantically believable, it is logically invalid. Hence it might lead to belief-bias, an extensively studied phenomenon in the psychology of thinking and reasoning (e.g. J. St. B. T. Evans et al., 1983). Thus, the validity of the conclusion is conditioned on the truth or falsehood of the premises. In Bayesian epistemology, the evidence is conditional, i.e., based on the empirical data at hand. Carl Sagan (as cited in Stephens, 2011) gives the following example for absent evidence reasoning: “Sherlock Holmes notices that a dog does not bark (absent evidence) and concludes that this is evidence that there is no criminal who is stranger—the culprit must have known the dog” (Sagan, 1997). The point Sagan wants to illustrate that reasoning of evidence leads to fallacious logical conclusions. For instance, we currently do not have evidence that alien intelligent life exists on other planets. Ergo, one might conclude that there is no intelligent life on other planets. Sagan argues that the lack of evidence does not poof the absence of alien life. On the other hand, the absence cocaine in a standard hair follicle test is evidence that the subject under investigation has not taken any cocaine recently.

However, a detailed discussion of “absent evidence reasoning” and the underlying cognitive processes goes beyond the scope of this chapter and we refer the interested reader to Stephens (2011).

From the point of view of statistical data analysis, Bayesian inference can be regarded as a from of probabilistic inference that reallocates belief (credibility) across a space of potential possibilities, i.e., a set of candidate culprits, to use the detective analogy (Kruschke et al., 2017). The analysist (or detective or judge) is confronted with noisy numerical data and tries to approximate the pattern with a mathematical model. “The space of potential suspects for describing the data is the space of values for the parameters” (Kruschke, 2013). In other words, potential suspects in legal scenario are equivalent to a specific (plausible) range of potential parameter values in a Bayesian descriptive model. The primary purpose of the Bayesian analysis is thus to specify a range of possibilities (plausible parameter values) in the form of *credibility intervals*.

Appendix E3 Mathematical foundations of Bayesian inference

Bayesian inference allocates credibility (i.e., belief) across the parameter space Θ[251] of the model (conditional on the *a priori* obtained empirical data). The mathematical axiomatic basis is provided by Bayes' theorem. Bayes' theorem derives the probability of θ given the empirical data in terms of its inverse probability (i.e., the probability of the data given θ and the prior probabilities of θ). In other word "Bayesian data analysis involves describing data by meaningful mathematical models, and allocating credibility to parameter values that are consistent with the data and with prior knowledge" (Kruschke & Vanpaemel, 2015, p. 279)

The mathematical formula for the allocation of credibility across parameters is axiomatized in Bayes' theorem (Bayes & Price, 1763), i.e., Bayes' theorem mathematically defines the posterior distribution on the parameter values in a formal manner.

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)}$$

Where:

- $P(A)$ signifies the prior (the preliminary belief about A)
- $P(B)$ signifies the evidence
- $P(A|B)$ signifies the posterior probability (the belief about of A given B)
- $P(B|A)$ signifies the likelihood.

[251]Uppercase Theta (Θ) denotes the set of all possible combinations of parameter values in a specific mathematical model (the joint parameter space). Lowercase theta (θ) on the other hand, denotes a single k-dimensional parameter vector.

Applied to the current analysis Bayes' theorem takes the following form:

$$\underbrace{p(\mu_1, \sigma_1, \mu_1, \sigma_1, \nu \mid D)}_{posterior} = \underbrace{p(D \mid \mu_1, \sigma_1, \mu_1, \sigma_1, \nu)}_{likelihood} \text{ x } \underbrace{p(\mu_1, \sigma_1, \mu_1, \sigma_1, \nu)}_{prior} \ / \underbrace{p(D)}_{evidence}$$

let D be the empirical data, μ_1 and μ_2 the means per experimental condition (e.g., condition V_{00} and V_{01}), σ_1 and σ_2 the associated standard deviations, and ν the normality parameter.

Bayes' theorem (Bayes & Price, 1763) as specified for the descriptive model used to estimate the parameters of interest in Experiment 2.

Bayes' theorem emphasises the posterior (conditional) distribution of parameter values (the Latin terminus *"a posteriori"* signifies empirical knowledge which proceeds from experiences/observations). The factors of Bayes' theorem have specific meaning assigned to them: The "evidence" for the specified model, *p(D)*, equals the total probability of the data under the model which can be computed by averaging over the parameter space Θ (Kruschke, 2015). Each parameter value is weighted by the "strength of belief" in the respective values of θ. For the current model, Bayes' theorem can be semantically summarised as follows: It signifies that the posterior probability of the combination of parameter values (i.e., $< \mu_1, \mu_2, \sigma_1, \sigma_2, \nu >$) is equal to the likelihood of that parameter value combination multiplied by the prior probability of that parameter combination, divided by the constant $p(D)$. This constant is often referred to as the "*evidence*" for the model and is also called the "*marginal likelihood function*" (Kruschke, 2013). Its numerical value is calculated by taking the average of the likelihood, $p(D|\theta)$, across all values of θ (i.e., over the entire parameter space Θ), weighted by the prior probability of θ (Kruschke, 2014). The posterior distribution is thus always a compromise between the prior believability of the parameter values and the likelihood of the parameter values, given data. (Kruschke, 2010b). Our experimental data was measured on a visual analogue scale (VAS) ranging across a continuum of values. Given the extremely fine-grained nature of our measurements the resulting numerical values are "quasi-continuous". Therefore, all parameters are regarded as continuous variables for all practical purposes. It thus follows that the posterior distribution is continuously distributed across the joint parameter space Θ (Kruschke et al., 2017).

Given that Bayesian parameter estimation (BPE) is currently no methodological standard in psychology we will provide some terminological clarifications of the underlying Bayesian nomenclature. The credibility of the parameter values after the empirical observation is termed the "posterior distribution", and the believability of the parameter values before the empirical observation is termed the "prior distribution". The probability of the observation for a particular parameter value combination, is called the "marginal likelihood function". It indicates the degree to which the observed outcome is anticipated, when averaged across all possible values of the weights, scaled proportionally to their respective believability (Kruschke, 2008). The denominator labelled as "evidence", $p(D)$, is the marginal likelihood also referred to as "model evidence". In BPE, Bayes' theorem is used to make inferences about distribution parameters, i.e., the conditional distribution of θ is calculated given the observed data. What is the probability of θ conditional on the observed data. The prior is an unconditional distribution associated with θ. In contrast to NHST, θ is not assumed to be random, we are merely nescient[252] of its value. In other words, probability is

[252] The term "nescienct" is a composite lexeme composed of the Latin prefix from *ne* "not" + *scire* "to know" (cf. "science"). It is not synonymous with ignorant because ignorance has a different semantic meaning ("to ignore" is very different from "not knowing").

conceptualised as a state of subjective belief or state of knowledge (as opposed to objective "pure" probability as an intrinsic characteristic of θ).

The posterior distribution is approximated by a powerful class of algorithms known as *Markov chain Monte Carlo* (MCMC) methods (named in analogy to the randomness of events observed at games in casinos). MCMC generates a large representative sample from the data which, in principle, allows to approximate the posterior distribution to an arbitrarily high degree of accuracy (as $t \to \infty$). The MCMC sample (or chain) contains a large number (i.e., > 1000) of combinations of the parameter values of interest. Our model of perceptual judgments contains the following parameters: $< \mu_1, \mu_2, \sigma_1, \sigma_2, \nu >$. In other words, the MCMC algorithm randomly samples a very large *n* of combinations of θ from the posterior distribution. This representative sample of θ values is subsequently utilised in order to estimate various characteristics of the posterior (Gustafsson et al., 2017), e.g., its mean, mode, standard deviation, etc. pp. The thus obtained sample of parameter values can then be plotted in the form of a histogram in order to visualise the distributional properties and a prespecified high density interval can be superimposed on the histogram.

Relatively recent advances in technology make these computationally demanding methods feasible. The combination of powerful microprocessor and sophisticated computational algorithms allows researchers to perform extremely powerful Bayesian statistical analyses that would have been very expensive only 15 years ago and virtually impossible circa 25 years ago. The statistical "Bayesian revolution" is relevant for many scientific disciplines (Beaumont & Rannala, 2004; S. P. Brooks, 2003; Gregory, 2001; Shultz, 2007) and the scientific method in general. This Kuhnian-paradigm shift (T. Kuhn, 1970) goes hand in hand with the Moore's law (G. E. Moore, 1965) and the exponential progress of information technologies (Kurzweil, 2005) (cf. Goertzel, 2007) and the associated ephemeralization[253] (Heylighen, 2008). This topic is discussed in greater detail in chapter xxx.

For the current Bayesian analysis, the parameter space Θ is a five-dimensional space that embeds the joint distribution of all possible combinations of parameter values (Kruschke, 2014). Hence exact parameter values can be approximated by sampling large numbers of values from the posterior distribution. The larger the number of random samples the more accurate the estimate. A longer MCMC chain (a larger sample) provides a more accurate representation (i.e., better estimate or higher resolution) of the posterior distribution of the parameter values (given the empirical data). For instance, if the number of MCMC samples is relatively small and the analysis would be repeated the values would be significantly different and, on visual inspection, the associated histogram would appear "edgy". With larger MCMC samples, the estimated values (on average) approximate the true values of the posterior distribution of the parameter values and the associated histogram becomes smoother (Kruschke, 2014). The larger the MCMC sample size the higher the accuracy because the sample size *n* is proportional to the "Monte Carlo Error" (MCE; i.e., accuracy is a function of MCMC sample size). To sum up, the MCMC approach clearly yields approximate parameter values and its accuracy depends on the number of values *n* that are used to calculate the average. Quantitative methods have been developed to measure the Monte Carlo Error "objectively" (Elizabeth Koehler, Elizabeth Brown, 2009), however, this intricate topic goes beyond the scope of this chapter. Of great relevance for our purpose is the fact that this analytic approach also allows to compute the credible difference of means between experimental conditions by computing $\mu_1 - \mu_2$ for every combination of

[253] A concept popularised by Buckminster Fuller which is frequently cited as an argument against Malthusianism.

sampled values. Moreover, BPE provides a distribution of credible effect sizes. The same distributional information can be obtained for the differences between σ_1 and σ_2 (and the associated distributional range of credible effect sizes). To sum up, BPE is currently one of the most effective statistical approaches to obtain detailed information about the various parameters of interest.

Appendix E4 Markov chain Monte Carlo (MCMC) methods

Markov Chain Monte Carlo have transformed science, particularly due to their relevance for probabilistic logical inferences. Monte Carlo methods (sometimes termed Monte Carlo experiments) are a class of computational algorithms that utilise repeated random sampling to calculate their statistical results. The theoretical considerations behind Monte Carlo methods are old, for an example see the Buffon-Laplace need problem (Buffon, 1777). The appellation “Monte Carlo” is frequently attributed to the quantum physicist John von Neumann (inter alia) and Monte Carlo methods have been discussed in many diverse scientific contexts (Behrends, 2014; Dell & Franklin, 2009; Diaconis, 1976). However, they are generally primarily applied to three broad classes of problems: mathematical optimization, numerical integration, and the generation of samples from probability distributions (Kroese, Brereton, Taimre, & Botev, 2014).
Markov chains are based on the stochastic foundations developed by the Russian mathematician Andreyevich Markov who extended the central limit theorem to sequences of random variables (hence the eponymous name “Markov chains”). In 1912, his work was translated into German under the title “Wahrscheinlichkeitsrechnung“, that is “probability calculus” (Markov, 1912). For a historical overview see Basharin, Langville, & Naumov (2004).
Markov chain Monte Carlo methods are based on the seminal work of the physicist

Nicholas Metropolis *et alia* (Metropolis, Rosenbluth, Rosenbluth, & Teller, 1953) who initially utilised the approach to simulated energy levels of atoms in crystalline structures[254]. The concept was later generalised by the statistician W. K. Hastings (1970). MCMC methods became more popular in the context of Bayesian inference due to the work of Gelfand and Smith (1990) who emphasised the relevance of MCMC methods to calculating Bayesian posterior densities. Recent computational advances have made them more accessible to researchers in various scientific disciplines (Diaconis, 2008; W. L. Dunn & Shultis, 2012). Today, the Metropolis–Hastings algorithm is one of the most widely used MCMC algorithm in statistics and in statistical physics. The Metropolis–Hastings algorithm comprises the construction of a Markov process which, in theory, results in a unique and stationary distribution. For a detailed mathematical derivation of the algorithm see Robert and Casella (2004). Gibbs sampling can be regarded as a special case of the Metropolis–Hastings algorithm . Hence, MCMC methods based on the Gibbs sampling enables the analyst to draw inferences from iterative simulations (Gelman & Rubin, 1992). The quality of MCMC sample improves as a function of the number of steps. MCMC methods thus provide sampling probability density functions which can be utilised to obtain parameter estimates with their probabilistic associated uncertainties. To be specific, the goal of the MCMC method is to obtain a large set of samples (θ^l, $l = 1, \ldots, L$) from the posterior distribution in order to be in a position to estimate the parameters in question with

[254] Currently, cutting-edge Monte Carlo-based methods are applied to simulate complex quantum systems. The application of Monte Carlo methods to quantum physics is termed "Quantum Monte Carlo" (QMC). QCM has been used to approximate the statistical properties of bosons and fermions and it comes in various flavours. However, its foundation is based on the original seminal publication by Metropolis et al. (1953) titled "Equation of State Calculations by Fast Computing Machines" in which the authors suggested that Monte Carlo methods could in principle be utilised for "calculating the properties of any substance" (p.1087). Simulated Quantum Annealing (SQA) is a Markov Chain Monte-Carlo algorithm that has been utilised to simulating quantum annealing. In addition, SQA can be applied to multidimensional combinatorial optimization problems and it has been argued that it inherits some of the advantages of quantum tunnelling (but see Crosson & Harrow, 2016).

reasonable accuracy. As a general heuristic rule, it has been stated that L =100 is sufficient for reasonable posterior estimates. (Gelman et al., 2004). A sample that is too small can lead to inaccurate statistical inference. Stopping rules have been developed (Gong & Flegal, 2016) and the size of the Monte Carlo sample effects the standard error. Several convergence diagnostics have been developed. The Monte Carlo Error (MCE) is the uncertainty which can be attributed to the fact that the number of simulation draws is always finite. In other words, it provides a quantitative index that represents the quality of parameter estimates. For more information on the Markov chain central limit theorem see Jones (2004). The MCSE package in R provides convenient tools for computing Monte Carlo standard errors and the effective sample size (James Flegal et al., 2017). Notice that relatively small MCSEs indicate high estimation precision level. The main idea is to terminate the simulation when an estimate is sufficiently accurate for the scientific purpose of the analysis. Many practitioners utilize convergence diagnostics and visual inspections to evaluate if the chain has been run long enough.

In sum, MCMC are utilised to estimate characteristics of a posterior distribution by constructing a Markov chain with the target as its equilibrium distribution.

Appendix E5 Software for Bayesian parameter estimation via MCMC methods

In order to conduct the Bayesian parameter estimation, we utilised several open-source software packages (all are all freely available on the internet). We created a website were the associated URLs are compiled: http://irrational-decisions.com/?page_id=1993

Analyses were entirely conducted in R using the "BEST" package (Kruschke, 2014). Best is an acronym for "Bayesian Estimation Supersedes the *t*-Test". Moreover, we installed JAGS "Just Another Gibbs Sampler" (Plummer, 2003, 2005) and RStudio (RStudio Team, 2016). BEST has numerous (recursive) reverse dependencies and reverse import dependencies which can be found with the code below. For example, it relies on the software BUGS[255] "Bayesian inference Using Gibbs Sampling" (Lunn, Spiegelhalter, Thomas, & Best, 2009; Spiegelhalter, Thomas, Best, & Lunn, 2014). The utilised programs have been described in great detail two recent textbooks on Bayesian analysis (Kruschke, 2010a, 2014).

[255] The BUGS project is hosted by the MRC Biostatistics Unit, University of Cambridge: https://www.mrc-bsu.cam.ac.uk/software/bugs/

Appendix E6 R code to find various dependencies of the "BEST" package.

```
install.packages("miniCRAN")

library("miniCRAN")

tags <- "BEST"

pkgDep(tags, suggests = TRUE, enhances = TRUE)
```

Code 11. R code to find various dependencies of the "BEST" package.

Appendix E7 Hierarchical Bayesian model

In order to carry out the Bayesian parameter estimation procedure, we first defined the prior distribution. The to be estimated parameters relevant for the hypotheses at hand were: the means μ_1 and μ_2; the standard deviation σ_1 and σ_2 and the normality parameter v. We were particularly interested in the a priori predicted difference between experimental conditions, i.e., $\mu_1 - \mu_2$. The main purpose of the Bayesian parameter estimation was thus to estimate these parameters and to quantify the associated uncertainty (i.e., credibility) of these approximations. We defined a descriptive model for the Bayesian parameter estimation which is outlined in the following subsection. We ascribed an appropriate prior distribution to all five parameters (see Figure 130). The prior distribution specified for each parameter is as follows: The empirical data (x) is described by a *t*-distribution (the wider tails make the t-distribution more robust compared to the Gaussian distribution, i.e., it is less sensitive to outliers). The *t*-distribution has three parameters: the mean (μ), the scale parameter (σ), and the degrees of freedom (v). Low values of v are associated with wider tails (v can be regarded as a "shape parameter"). As v get larger the t-distribution converges to a Gaussian (see Figure 131 and Figure 132).

In order to make the prior distribution tolerable for a sceptical audience we chose very unspecific priors which signify a lack of prior knowledge about the conceivable values of the parameters of interest. Defining the prior distribution in such vague (noncommittal) terms indicates that it has a negligible impact on the estimation of the posterior distribution. In other words, by choosing noninformative priors we ensured that the data governs the inference.

All priors were specified according to the model detailed in Kruschke (2013). The prior distribution of μ_1 and μ_2 was defined as a very broad normal distribution in the model. The standard deviation S of the prior distribution of μ_1 and μ_2 was arbitrarily defined as 1000 times the standard deviation of both conditions (i.e., SD_{pooled}). Moreover, the mean M of the prior distribution was defined in the same way (1000*pooled $\bar{x}pooled \sim N\{\mu, \frac{\sigma^2}{pooled}\}$). The prior of the standard deviation parameters σ_1 and σ_2 was likewise defined with noncommittal characteristics, ranging from a low value L (one thousands of the standard deviation of the pooled conditions) to a high value H. We ascribed an exponentially distributed prior to ν parameter. This configuration distributes prior credibility relatively homogenously over Gaussian and heavy-tailed data distributions. In doing so we followed the recommendation described in (Kruschke, 2013, Appendices A and B). For precise mathematical derivations see Krusckke (2014).

Appendix E8 Definition of the descriptive model and specification of priors

The parameters $\mu1$ and $\mu2$ are modelled by a normal distribution. In concordance with Kruscke (2013) the standard deviation of μ was expressed in very broad terms (SDpooled x 1000). The mean M of the prior distribution of μ was defined a M_{pooled} (the pooled mean of the empirical data). The prior distribution for σ_1 and σ_2 was also noninformative, i.e., a wide uniform distribution with hyperparameters ranging from L=SDpooled /1000 to H $1000 \times SD_{pooled}$. In practical terms, the resulting priors are extremely wide and approximate a uniform distribution raging from $-\infty$ to ∞. Lastly, the prior distribution for a shifted exponential (λ=29, shifted+1) was defined for the normality index ν (for mathematical details see Kruschke, 2013, Appendix A). As a simplifying assumption, it is postulated that the degree of normality ν is equivalent for both experimental conditions. The probabilistic model is visualised in Figure 130.

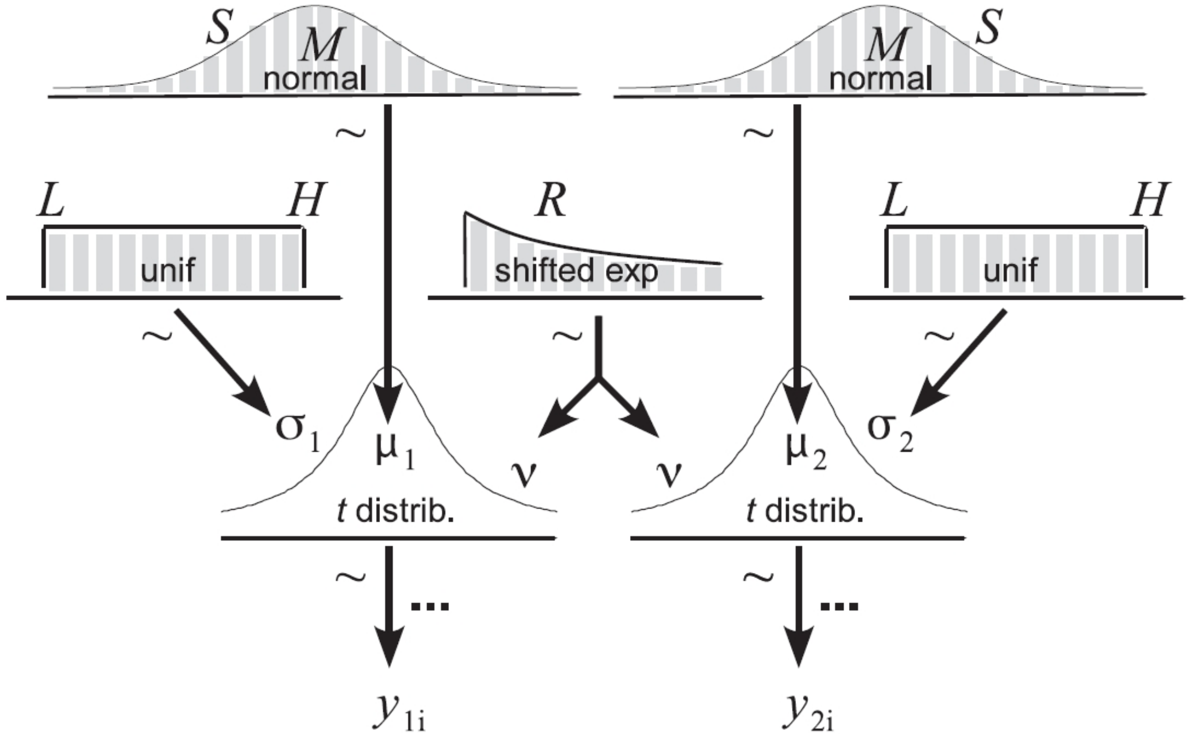


Figure 130. Hierarchically organised pictogram of the descriptive model for the Bayesian parameter estimation (adaptd from Kruschke, 2013, p. 575).

The experimental data from condition V_{00} (yli) and V_{01} (y2i) are located at the bottom of the pictogram. These data are described by heavy tailed and broad (noncommittal) *t*-distributions[256]. The data are randomly distributed (~) and the conditions have unique parameters for the respective means and standard deviations, i.e., μ_1, μ_2, and σ_1, σ_2, correspondingly. The parameter for the normality index *v* is equivalent and thus shared between conditions. Summa summarum, we defined four unique types of distributions for the five-dimensional parameter space Θ. The respective distributions were parametrised in such a way that prior commitment has a minimal impact on the posterior (i.e., we adopted a non-informative "objective" Bayesian approach).

[256] Note that the t-distribution is stipulated as the distribution for the data. By contrast, the NHST t-test utilises the t-distribution as a distribution of the sample mean divided by the sample standard deviation.

Legend:

- S = standard deviation;
- M = mean;
- L =low value;
- H = high value;
- R = rate;
- unif = uniform;
- Shifted exp = shifted exponential;
- distrib. = distribution

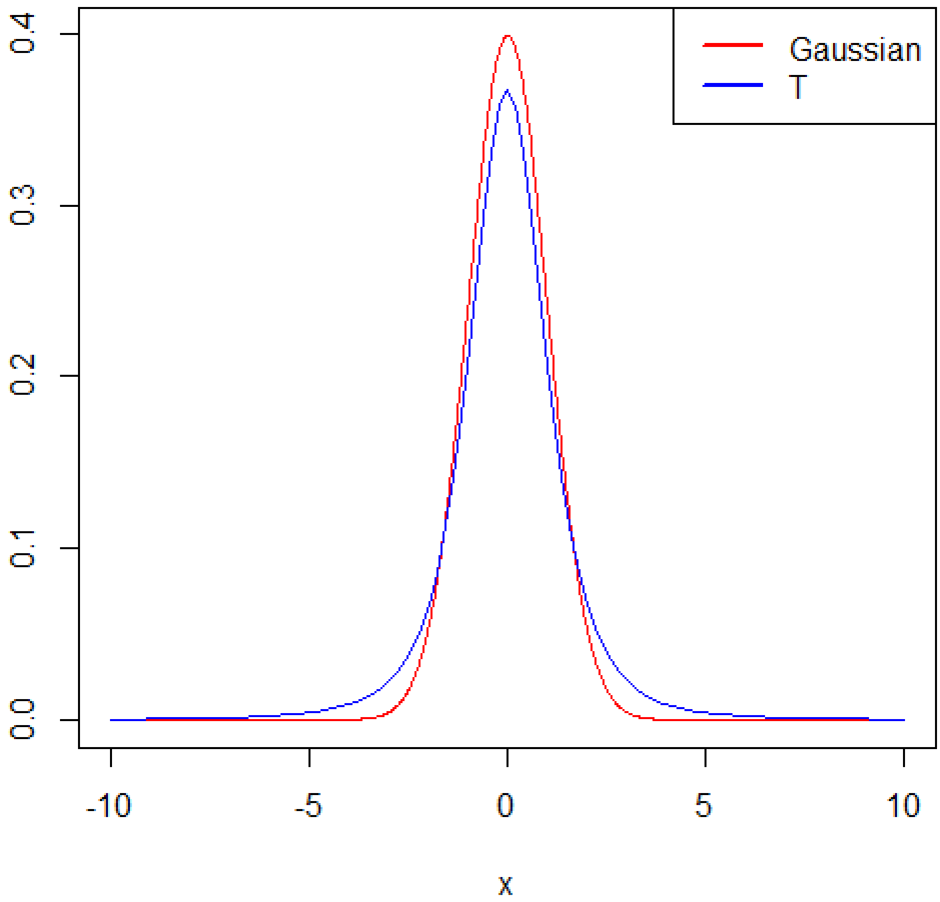


Figure 131. Visual comparison of the Gaussian versus Student distribution.

```
curve(dnorm(x), -10, 10, n=1000, col = "red", ylab="")

curve(dt(x, df = 3), col = "blue", add = TRUE)

legend("topright", c("Gaussian","T"),

  lty=c(1,1,1), # symbols (lines)

  lwd=c(2,2,2), col=c("red", "blue"))
```

Code 12. R code for visualising a Gaussian versus Student distribution.

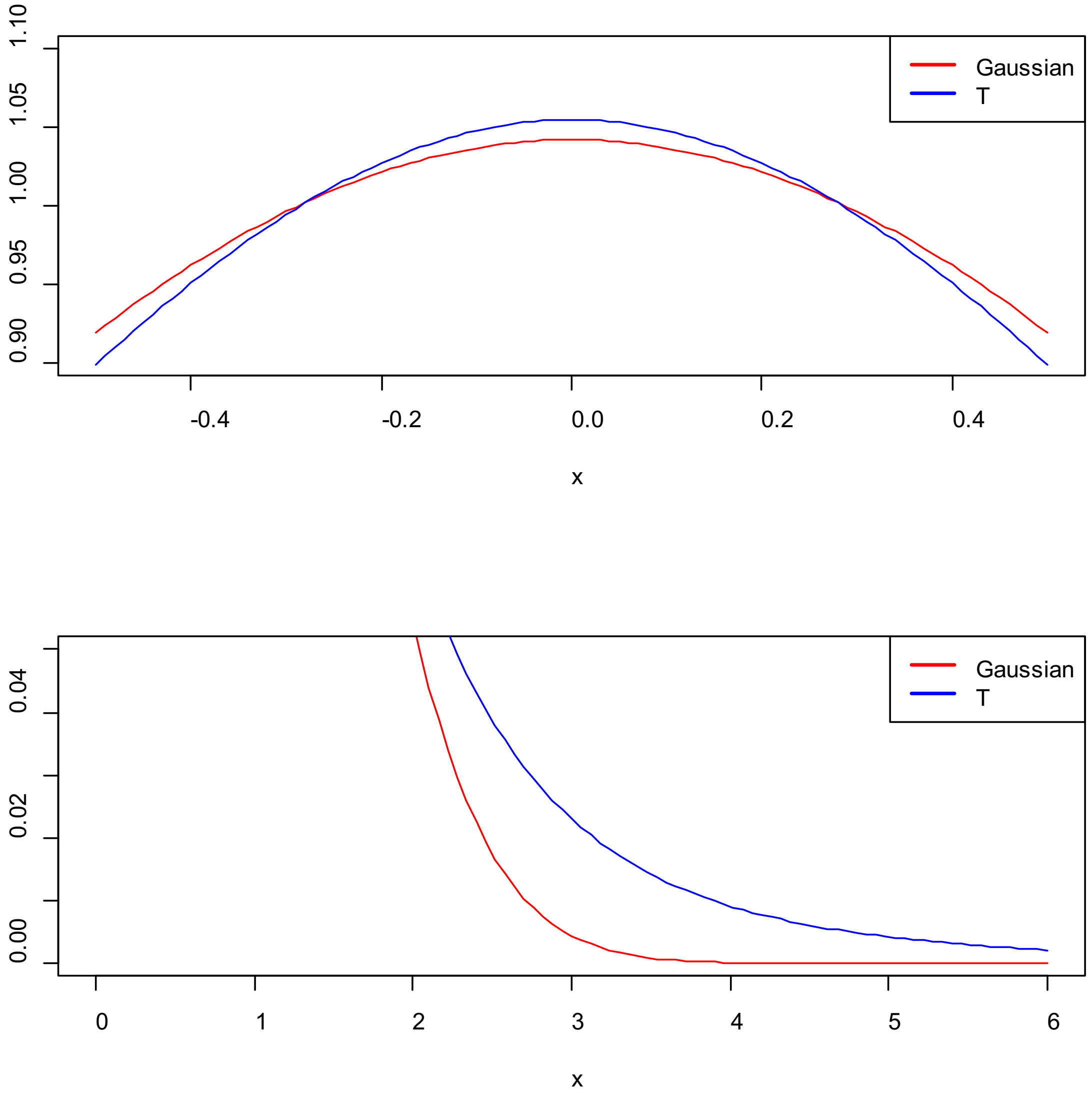


Figure 132. Visual comparison of the distributional characteristics of the Gaussian versus Student distribution.

```
layout(matrix(c(1,1,2,2), 2, 2, byrow = TRUE))

df <- 3

a <- 0.5

cond_norm_dist <- function(x) dnorm(x)/(pnorm(a) - pnorm(-a))

cond_t_dist <- function(x) dt(x, df = df)/(pt(a, df = df) - pt(-a,

   df = df))

curve(cond_norm_dist(x), -a, a, col = "red", ylab="")

curve(cond_t_dist(x), col = "blue", add = TRUE)

legend("topright", c("Gaussian","T"),

  lty=c(1,1,1), # symbols (lines)

  lwd=c(2,2,2), col=c("red", "blue"))


#zoom in on tail to emphasise heavy tail of t distribution

low <- 0; high <- 6

curve(dnorm(x),  from = low, to = high, ylim = c(0, .05), col = "red", ylab="")

curve(dt(x, df = 3), col = "blue", add = TRUE)

legend("topright", c("Gaussian","T"),

  lty=c(1,1,1), # symbols (lines)

  lwd=c(2,2,2), col=c("red", "blue"))
```

Code 13. R code for detailed comparison of differences between the Gaussian and the superimposed *t*-distribution.

As can be seen in Figure 131 and Figure 132 the Student *t*-distribution (invented by Gosset, 1908; a.k.a. Student)[257] is more centred around 0. In comparison to the Gaussian distribution, the *t*-distribution has heavy tails. The height of the tails is denoted by the Greek letter ν (nu). A heavy-tailed distribution has a large ν (e.g., a value of 90). A small ν on the other hand, signifies an approximation of the Gaussian distribution.

[257] For a historical discussion see Fisher-Box (1987; 1981) and Neyman (1938).

Hence, ν can be regarded as a quantitative tail-index of a given probability density function. If ν has a small parameter, the distribution can represent data with outliers very well. In the subsequent analysis, data from each experimental condition will be described with a *t* distribution. Each condition has its individual mean and standard deviation. Because we did not observe many extreme values (i.e., spurious outliers) we will use an identical tail-index ν for both conditions. In sum, we will utilise Bayesian estimation for the following five parameters: μ_1, μ_2, σ_1, σ_2, and ν.

Appendix E9 Summary of the model for Bayesian parameter estimation

The specified model describes the data with five parameters: < μ_1, μ_2, σ_1, σ_2, ν >. The priors were very vaguely defined. Noncommittal priors have the advantage that the parameter estimates are primarily determined by the empirical data (i.e., bottom-up/data driven inference) and not by *a priori* theoretical considerations which might bias the model. The analysis will produce thus produce five parameter estimates that are statistically plausible given the experimental data at hand.

We parametrised the model with default (noninformative priors), specifically we defined normal priors with a large minimally informative standard deviation for μ, uniform minimally informative priors for σ, and an minimally informative exponential prior for v. Mathematical details about this specification are provided in chapter 11 and 12 in (Kruschke, 2015).

Appendix E10 MCMC computations of the posterior distributions

Bayesian posterior probabilities were calculated via Markov chain Monte Carlo sampling in order to compare differences between experimental conditions. We executed the program in the following way:

1. We loaded the function “BEST.R” into R's working memory (the function has several dependencies and several programmes need to be installed in advance, e.g., it relies on JAGS and BUGS and RStudio should be installed).
2. The experimental data was downloaded from the specified URL and formatted into the first two condition (V00 and V01) were converted into vectors.
3. A MCMC chain of the length of 100,000 was generated
4. The results were plotted
5. The numerical output was generated

The associated R code can be downloaded from the following URL: http://irrational-decisions.com/?page_id=1996

Reproducible analysis scrips for the simulations and analyses are available under the following URL: http://irrational-decisions.com/phd-thesis/

```
##########################################################################
#######
### To run this program, please prepare your computer as follows.
### 1. Install the general-purpose programming language R from
###      http://www.r-project.org/
###    Install the version of R appropriate for your computer's operating
###    system (Windows, MacOS, or Linux).
### 2. Install the Bayesian MCMC sampling program JAGS from
###      http://mcmc-jags.sourceforge.net/
###    Again, install the version appropriate for your operating system.
### 3. Install the R editor, RStudio, from
###      http://rstudio.org/
###    This editor is not necessary, but highly recommended.
### 4. Make sure that the following programs are all
###    in the same folder as this file:
###      BESTexample.R (this file)
###      BEST.R
###      DBDA2E-utilities.R
###      BESTexamplePower.R
### 5. Make sure that R's working directory is the folder in which those
###    files reside. In RStudio, use menu tabs Tools -> Set Working Directory.
###    If working in R, use menu tabs File -> Change Dir.
### 6. After the above actions are accomplished, this program should
###    run as-is in R. You may "source" it to run the whole thing at once,
###    or, preferably, run lines one at a time in order.
##########################################################################
#######
```

```
#clears all of R's memory
rm(list=ls())
# Get the functions loaded into R's working memory
# The function can also be downloaded from the following URL:
# http://irrational-decisions.com/?page_id=1996

source("BEST.R")
#download data from server
dataexp2 <-
 read.table("http://www.irrational-decisions.com/phd-thesis/dataexp2.txt",
        header=TRUE, sep="", na.strings="NA", dec=".", strip.white=TRUE)
# Specify data as vectors
y1 = c(dataexp2$v00)
y2 = c(dataexp2$v01)
# Run the Bayesian analysis using the default broad priors described by Kruschke (2013)
mcmcChain = BESTmcmc( y1 , y2 , priorOnly=FALSE ,
              numSavedSteps=12000 , thinSteps=1 , showMCMC=TRUE )
postInfo = BESTplot( y1 , y2 , mcmcChain , ROPEeff=c(-0.1,0.1) )
```

Code 14. R code for Bayesian analysis using the "BEST.R" function.

The function "`BEST.R`" can be downloaded from the CRAN (Comprehensive R Archive Network) repository under https://cran.r-project.org/web/packages/BEST/index.html or from our website under the following URL: http://irrational-decisions.com/?page_id=1996

Alternatively, the BEST function has been ported to MATLAB[258] and Python.[259]

The BEST core function (BESTmcmc) was implemented to obtain the Monte Carlo based estimations of all posterior quantities of interest. In order to achieve a robust (stable) MCMC approximation of the posterior, we specified a Markov chain length of 100,000. We saved a total length of 12,000 after adaption of 500 steps and burn-in of 1000 steps. Moreover, we thinned the chain by 5 to counteract autocorrelation. This procedure resulted in a data matrix of 1200 rows and 5 columns, i.e., one column for each of the five parameters of interest $< \mu_1, \mu_2, \sigma_1, \sigma_2, \nu >$. In order to ensure that the MCMC approach yields and accurate representation of the posterior distribution we conducted several diagnostic tests of convergence which are reported in the following subsection.

[258] Matlab version of BEST: https://github.com/NilsWinter/matlab-bayesian-estimation/

[259] Python version of BEST: https://github.com/strawlab/best/

Appendix E11 MCMC convergence diagnostics

To visualise the dataset which resulted from the MCMC sampling we created a 3D-scatterplot. The resulting graphics are depicted in Figure 122. The depiction of the entire parameter space Θ would require a 5-dimensional representation which is obviously impossible to visualise.

Gibbs sampling is a Markov chain Monte Carlo algorithm for obtaining a sequence of random samples (based on a random walk model) from a priori defined probability distribution. Specifically, Gibbs sampling is a special case of the Metropolis-Hastings algorithm (Hastings, 1970). Gibbs sampling is a widely used methods in the context of Bayesian inferential statistics.

As discussed previously in the context of quantum probability and superposition (Chapter xxx), a (first-order) Markov process is a memoryless random walk (no memory of the previous state), i.e., its past and future states are stochastically independent (Gagniuc, 2017). A sequential succession of such steps is a Markov chain (eponymously named after Andrey Markov).

The MCMC method used in the subsequent analysis to automatically fine-tune the Markov chain parameters is based on an adaptive Metropolis-within-Gibbs algorithm. A detailed description of the mathematical underpinnings of this method is given by (G. O. Roberts & Rosenthal, 2009). Theoretically (based on the law of large numbers), as time approximates infinity ($t \rightarrow \infty$) a given Markov chain will converge to a stationary distribution (after the prespecified burn-in period (Geman & Geman, 1984)). This stationary distribution is also called the equilibrium distribution. In Bayesian inferential statistics, the equilibrium distribution forms the posterior distribution.

Appendix E12 Diagnostics

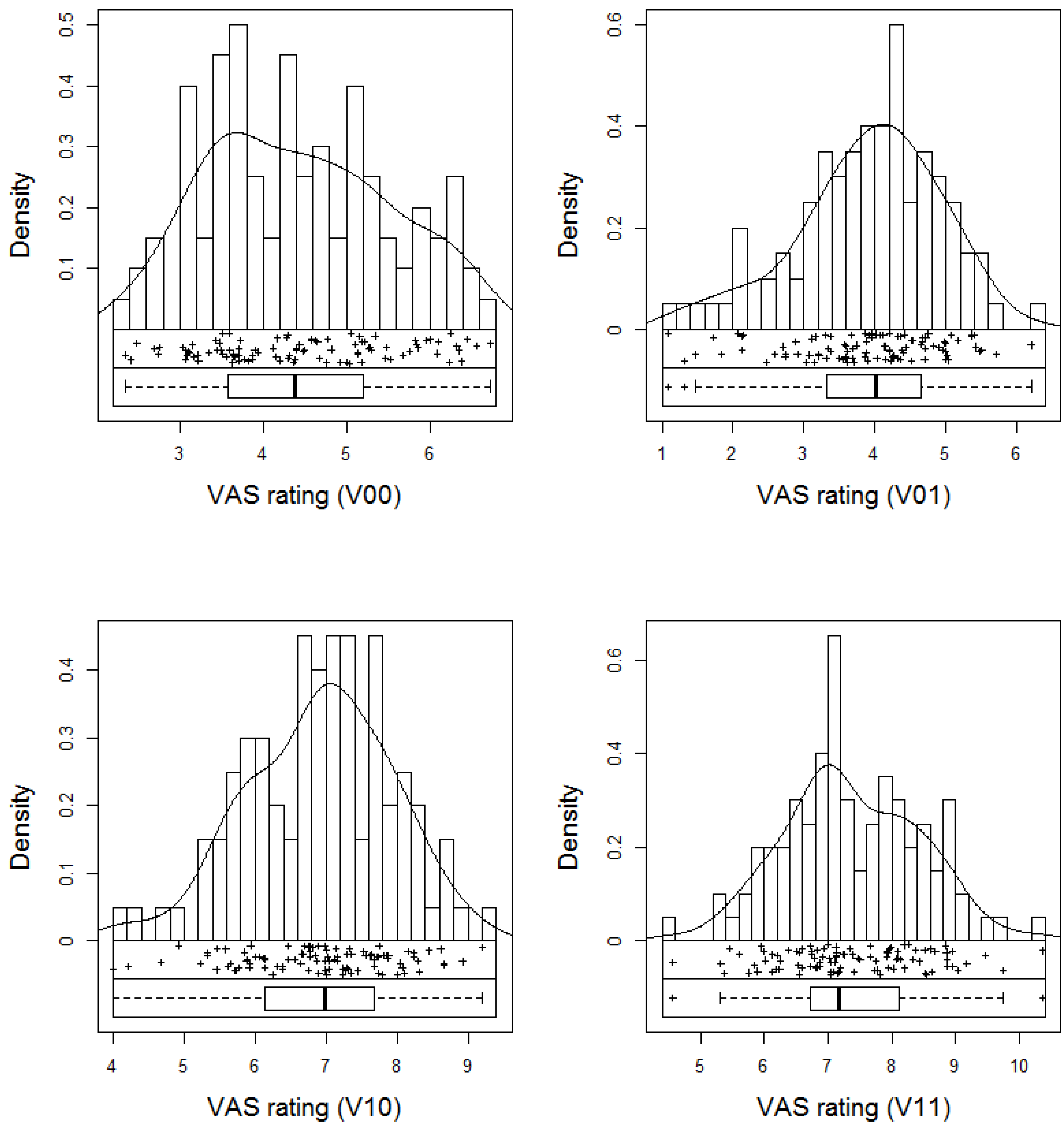


Figure 133. Edaplot created with "`StatDA`"[260] package in R.

Appendix E13 Probability Plot Correlation Coefficient Test

[260] URL: https://cran.r-project.org/web/packages/StatDA/StatDA.pdf

After (Filliben, 1975)

data: dataexp4$v00 ppcc = 0.98922, n = 100, p-value = 0.0938 alternative hypothesis: dataexp4$v00 differs from a Normal distribution
data: dataexp4$v01 ppcc = 0.98878, n = 100, p-value = 0.0857 alternative hypothesis: dataexp4$v01 differs from a Normal distribution
data: dataexp4$v10 ppcc = 0.99521, n = 100, p-value = 0.6184 alternative hypothesis: dataexp4$v10 differs from a Normal distribution
data: dataexp4$v11 ppcc = 0.99637, n = 100, p-value = 0.806 alternative hypothesis: dataexp4$v11 differs from a Normal distribution

Appendix E14 P_{rep} function in R

Its primary objective is to provide an estimate of replicability (based on the empirical data) which does not involve Bayesian assumptions with regards to *a priori* distributions of θ. The submission guidelines of the APA flagship journal Psychological Science for some time explicitly encouraged authors to "use p_{rep} rather than p-values" in the results section of their articles. This factoid is documented in the internet archive,[261] a digital library which provides a mnemonic online system containing the history of the web, a "digital time machine" (Rackley, 2009; Rogers, 2017). However, this official statistical recommendation by Psychological Science has now been retracted (but the internet never forgets…). By default, the p_{rep} metric is based upon a one-tailed probability value of test statistic T (but it can be used for F-test as well). However, this default can be changed into a two-tailed computation. We used the "`psych`" package (Revelle, 2015) in R to compute the replication probabilities (two-tailed) according to the following equation (the associated R code can be found below).

$$p_{\text{rep}} = [1 + (\frac{p}{1-p})^{\frac{2}{3}}]^{-1}$$

However, the mathematical validity of p_{rep} has been questioned (Doros & Geier, 2005). Based on the results of simulation studies, it has been convincingly argued that "p_{rep} misestimates the probability of replication" and that it "is not a useful statistic for psychological science" (Iverson et al., 2009). In another reply to Killeen's proposal, it has been suggested that hypothesis testing using Bayes factor analysis is a much more effective strategy to avoid the problems associated with classical p-values (E.-J.

[261] The URL of the relevant internet archive entry is as follows. https://web.archive.org/web/20060525043648/http://www.blackwellpublishing.com/submit.asp?ref=0956-7976

Wagenmakers & Grünwald, 2006). One of the main shortcoming of the suggested new metric is that p_{rep} does not contain any new information over and above the p-value, it is merely an extrapolation. Another weakness is that *a priori* information (for example knowledge from related previous studies) cannot be incorporated. Killeen responds to this argument with the "burden of history" argument, i.e., each result should be investigated in isolation without taking any prior knowledge into account (viz., he advocates uniform priors). However, it is highly questionable whether a single study can be used as a basis for estimating the outcome of future studies. Various confounding factors (e.g., a *tertium quid*) might have biased the pertinent results and consequently lead to wrong estimates and predictions. Extraordinary claims require extraordinary evidence. The novel p_{rep} metric does not align with this Bayesian philosophy. From our point of view, the main advantage to report and discuss p_{rep} is that it helps to explicate and counteract the ubiquitous "replication fallacy" (G Gigerenzer, 2004) associated with conventional p-value. The replication fallacy describes the widespread statistical illusion that the p-value contains information about the replicability of experimental results. In our own survey at a CogNovo workshop the "replication fallacy" was the most predominant misinterpretations of p-values. 77% (i.e., 14 out of 18) of our participants (including lecturers and professors) committed the replication fallacy. Only one participant interpreted the meaning of p-values correctly, presumably due to random chance. In a rejoinder titled "Replicability, confidence, and priors" (Killeen, 2005b) Killeen addresses several criticisms in some detail, particularly with regards to the stipulated nescience[262] of δ. Indeed, it has been argued that "replication probabilities

---

[262] In the semantic context at hand, nescience (etymologically derived from the Latin prefix *ne* "not" + *scire* "to know" cf. science) means "lacking knowledge" which is a more appropriate term than ignorance (which describes an act of knowingly ignoring). Unfortunately, linguistic diversity is continuously declining. A worrisome trend which is paralleled by a loss of cultural and biological diversity (Maffi, 2005; Worm et al., 2006b), *inter alia*.

depend on prior probability distributions" and that Killeen's approach ignores this information and as a result, "seems appropriate only when there is no relevant prior information" (Macdonald, 2005). However, in accordance with the great statisticians of this century (e.g., Cohen, 1994, 1995; Meehl, 1967), we argue that the underlying syllogistic logic of *p*-values is *inherently flawed* and that *any* attempt to rectify *p*-values is moribund. It is obvious that there is an urgent and long due "need to change current statistical practices in psychology" (Iverson et al., 2009). The current situation is completely intolerable and the ramifications are tremendously wide and complex. New and reflective statistical thinking is needed, instead of repetitive "mindless statistical rituals," as Gerd Gigerenzer[263] put it (G Gigerenzer, 1998, 2004). However, deeply engrained social (statistical) norms are difficult to change, especially when large numbers of researchers have vested interests to protect the prevailing methodological *status quo* as they were predominantly exclusively trained in the frequentist framework (using SPSS). Hence, a curricular change is an integral part of the solution. Statistical software should by default be flexible enough to perform multiple complementary analyses. SPSS is now capable to interface with R and various Bayesian modules will become available in future versions. This extension of capabilities could have been realised much earlier and one can only speculate why SPSS is non-Bayesian for such a long time. However, given that R is on the rise, SPSS is now forced to change its exnovative approach in order to defend market shares.

To conclude this important topic, it should be emphasised that rational approaches vis-

[263] Gigerenzer is currently director of the "Center for Adaptive Behavior and Cognition" at the Max Planck Institute in Berlin. In his article entitled "Mindless Statistics" Gigerenzer is very explicit with regards to the NHST ritual: "*It is telling that few researchers are aware that their own heroes rejected what they practice routinely. Awareness of the origins of the ritual and of its rejection could cause a virulent cognitive dissonance, in addition to dissonance with editors, reviewers, and dear colleagues. Suppression of conflicts and contradicting information is in the very nature of this social ritual*." (G Gigerenzer, 2004, p. 591)

à-vis problems associated with replicability, confidence, and the integration of prior knowledge are pivotal for the evolution and incremental progress of science. It is obvious that the fundamental methods of science are currently in upheaval.

1st comparison

$p.rep [1] 0.98626 $dprime [1] 0.6874459 $prob [1] 0.000910971 $r.equiv [1] 0.3250569

2nd comparison

$p.rep[1] 0.9763966$dprime[1] 0.6235255$prob[1] 0.002504747$r.equiv[1] 0.2976337

p.rep
Probability of replication
Dprime D'
Effect size (Cohen`s d) if more than just p is specified
prob
Probability of F, t, or r. Note that this can be either the one-tailed or two tailed probability value.
r.equivalent
For t-tests, the r equivalent to the t (see Rosenthal and Rubin(2003), Rosnow, Rosenthal, and Rubin, 2000))
The effect size estimate *r.equivalent* has been suggested by several authors (Rosenthal & Rubin, 2003; Rosnow, Rosenthal, & Rubin, 2000). It is particularly useful for meta-analytic research. However, it has been criticised on several grounds (Kraemer, 2005). The question of “what should be reported” standardised or simple effect size (Baguley, 2009b) is not resolved.
https://www.rdocumentation.org/packages/psych/versions/1.7.8/topics/p.rep

The associated R function can be found below:

```
function (p = 0.05, n = NULL, twotailed = FALSE)
{
    df <- n - 2
    if (twotailed)
        p <- 2 * p
    p.rep <- pnorm(qnorm((1 - p))/sqrt(2))
    if (!is.null(n)) {
        t <- -qt(p/2, df)
        r.equiv <- sqrt(t^2/(t^2 + df))
        dprime = 2 * t * sqrt(1/df)
        return(list(p.rep = p.rep, d.prime = dprime, r.equiv = r.equiv))
    }
    else {
        return(p.rep)
    }
}
<bytecode: 0x0000000015c932f8>
<environment: namespace:psych>
```
Code 15. “p.rep” function from the “psych” R package (after Killeen, 2005a)

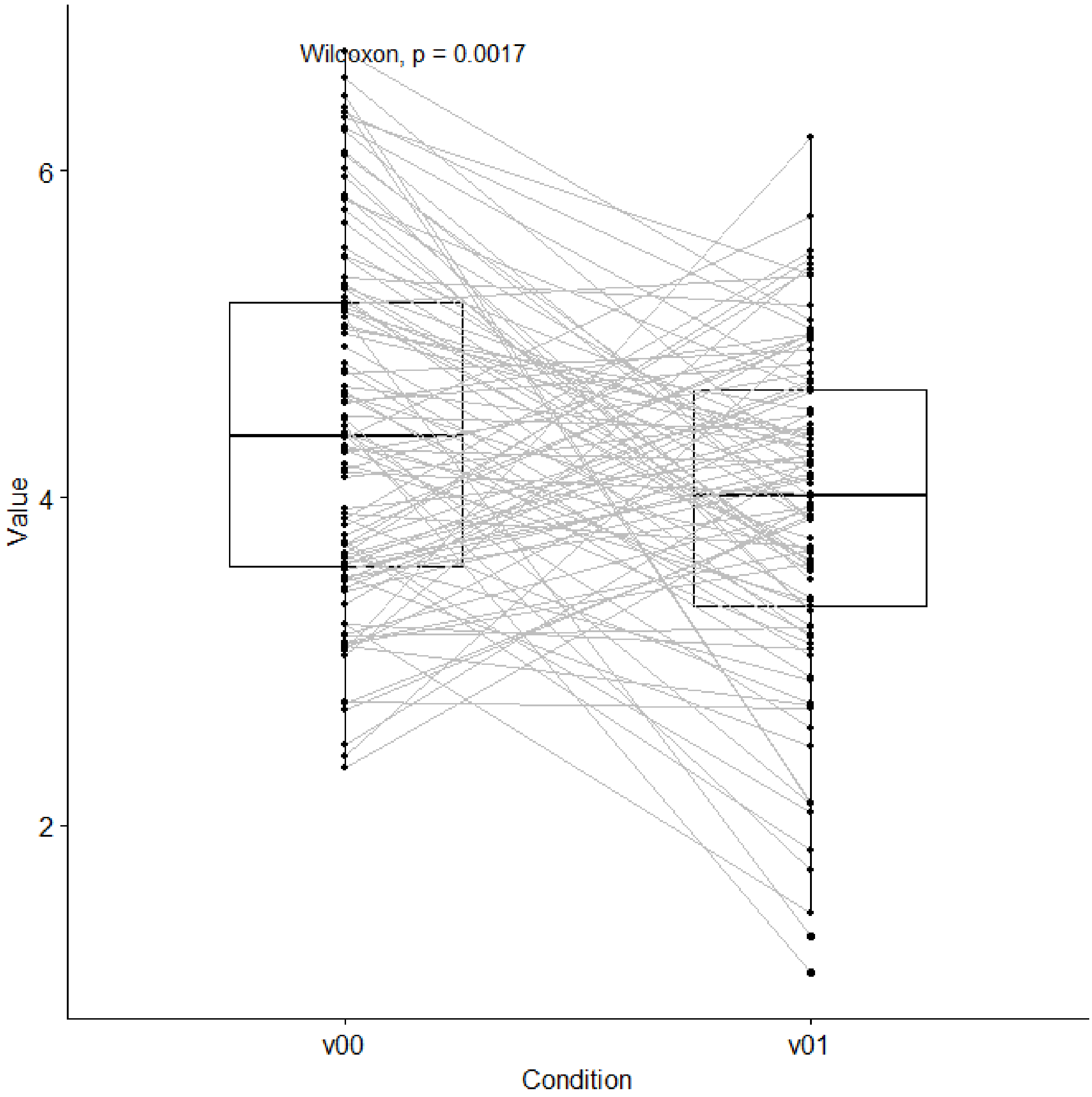


Figure 134. Connected boxplots for condition V_{00} vs. V_{01}.

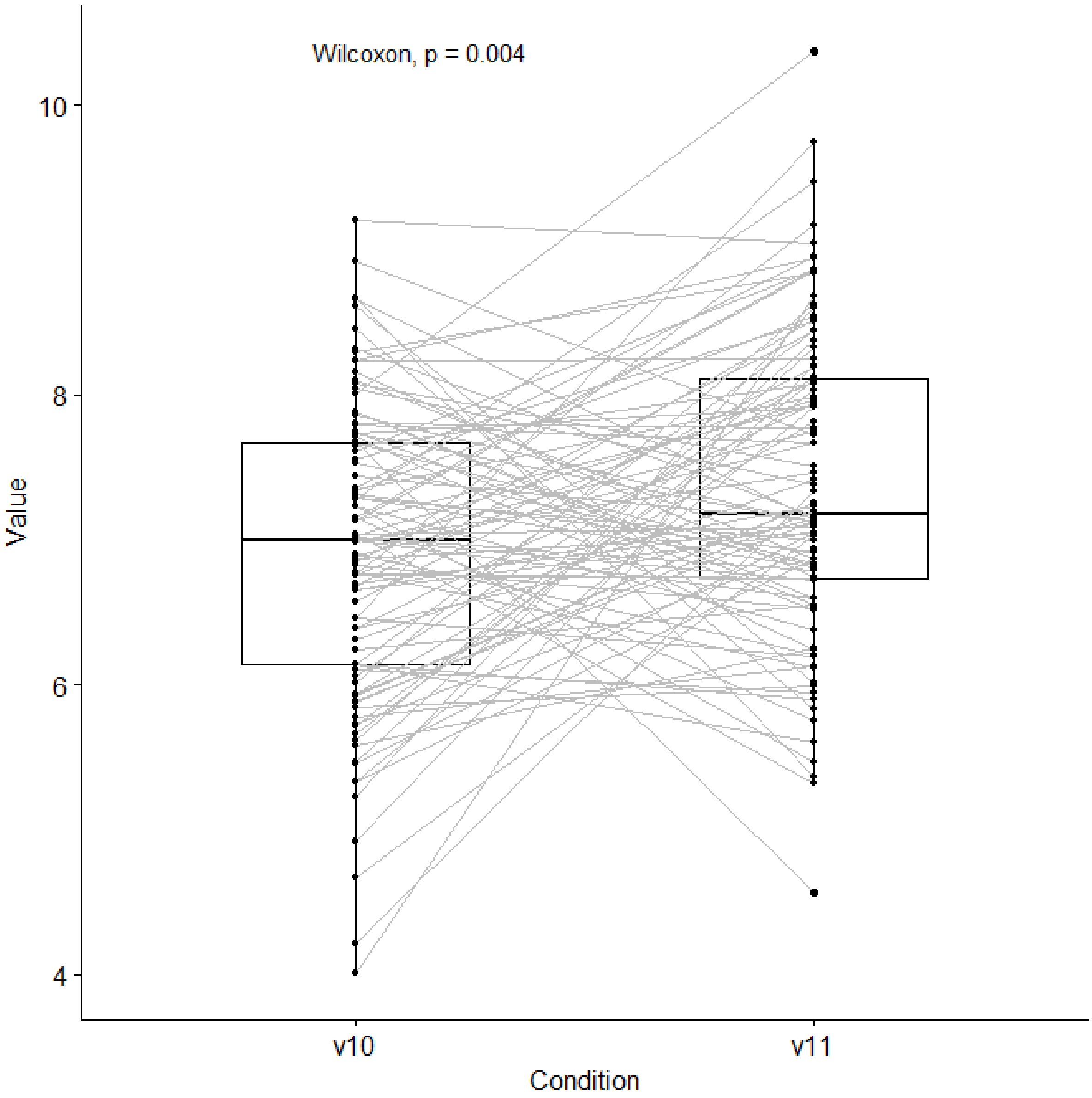


Figure 135. Connected boxplots for condition V_{10} vs. V_{11}.

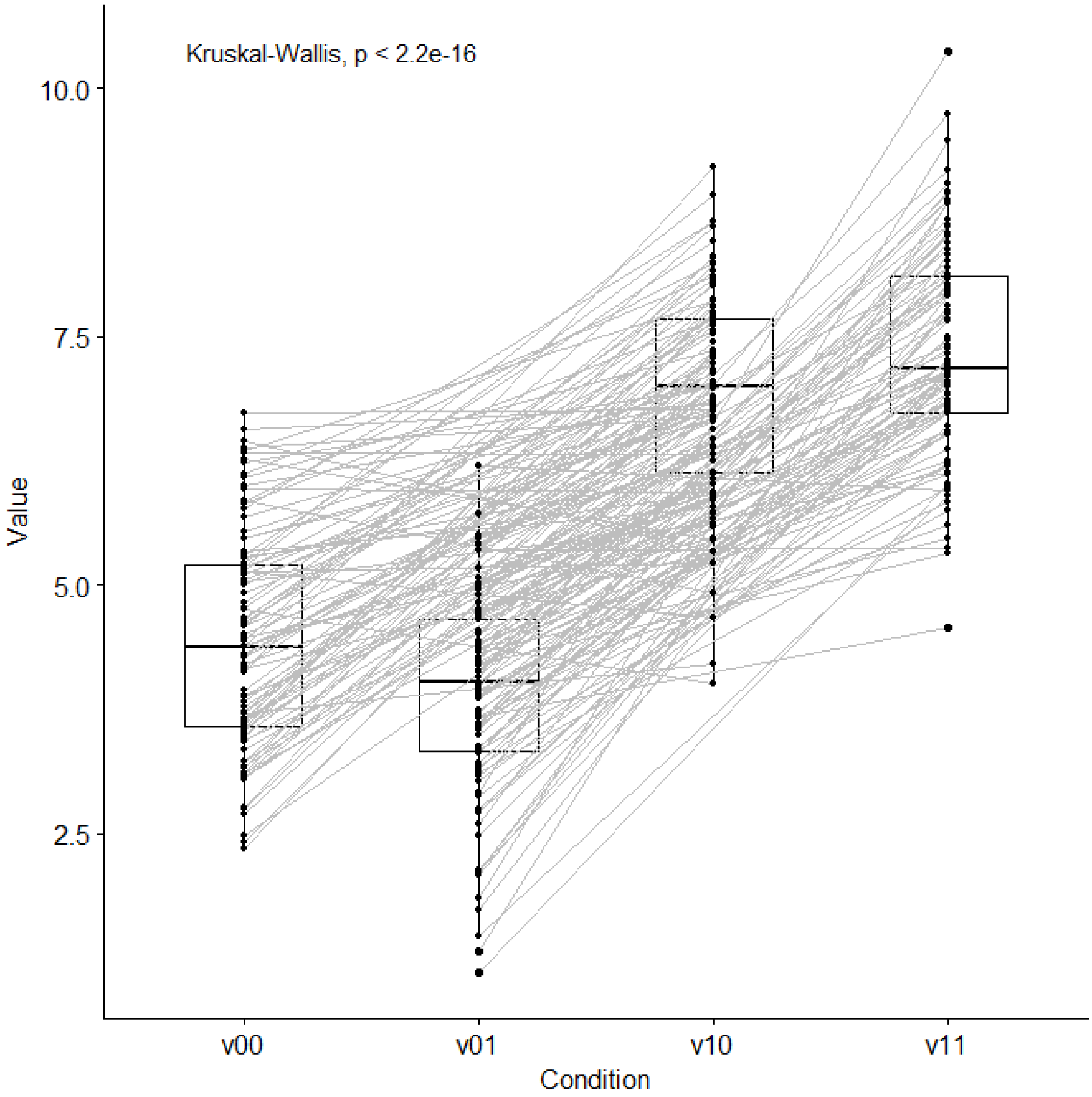
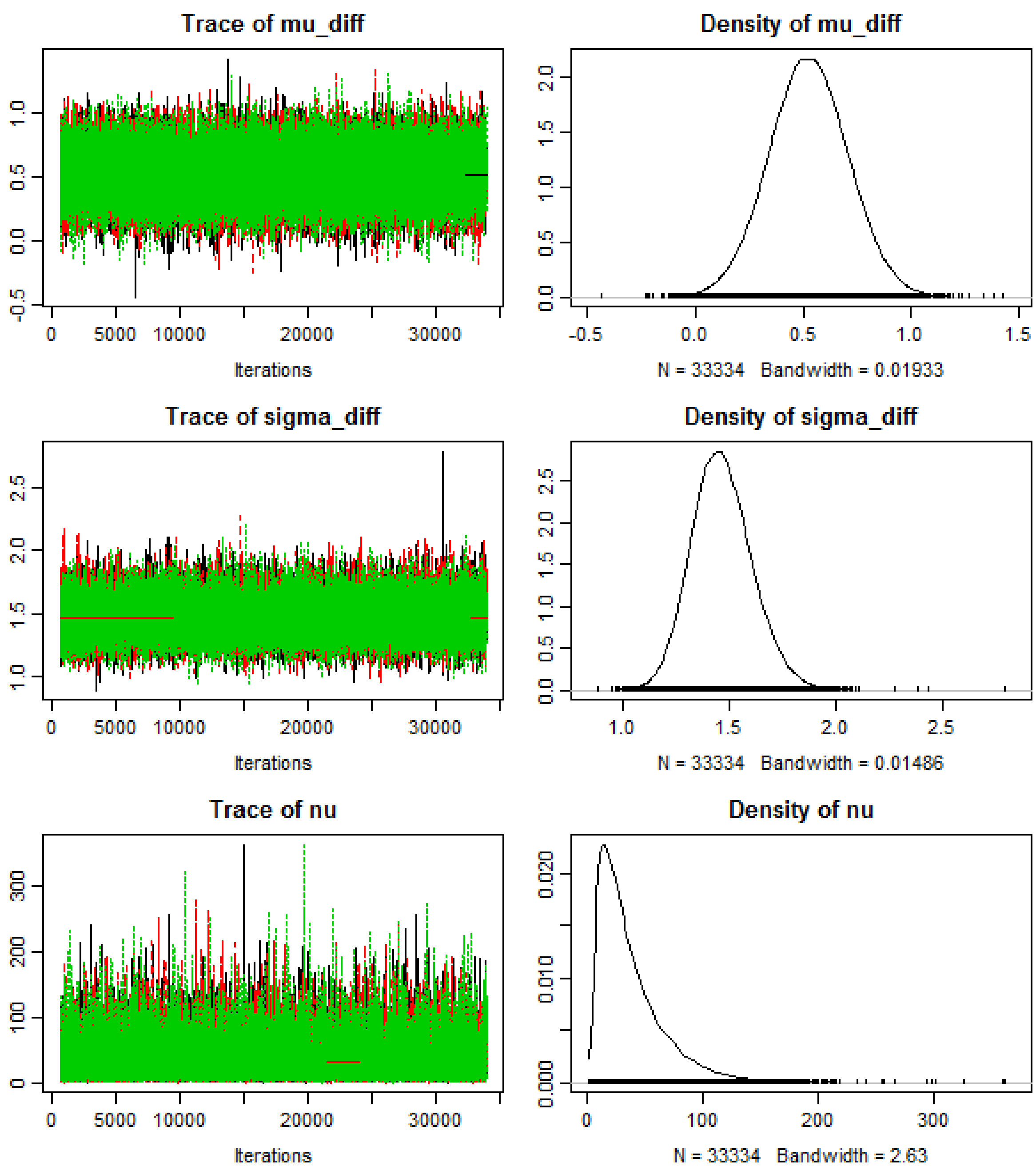


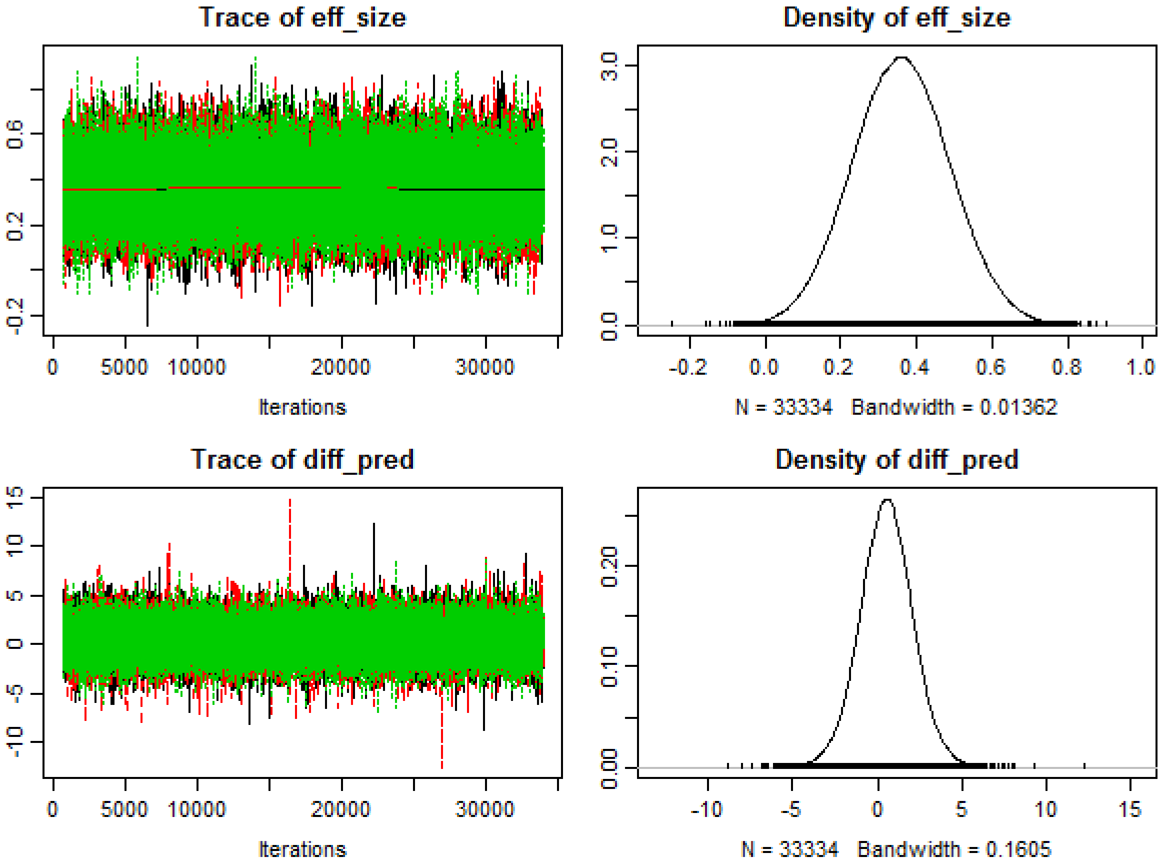
Figure 136. Connected boxplots for condition V_{00}, V_{01}, V_{10}, V_{11}.

Appendix E15 MCMC convergence diagnostic

This appendix contains the MCMC convergence diagnostic (i.e., ESS and MCSE) for all parameters. The graphics show the trace plot, autocorrelation plot, shrink factor plot, and the density plot.

V_{00} vs. V_{01}

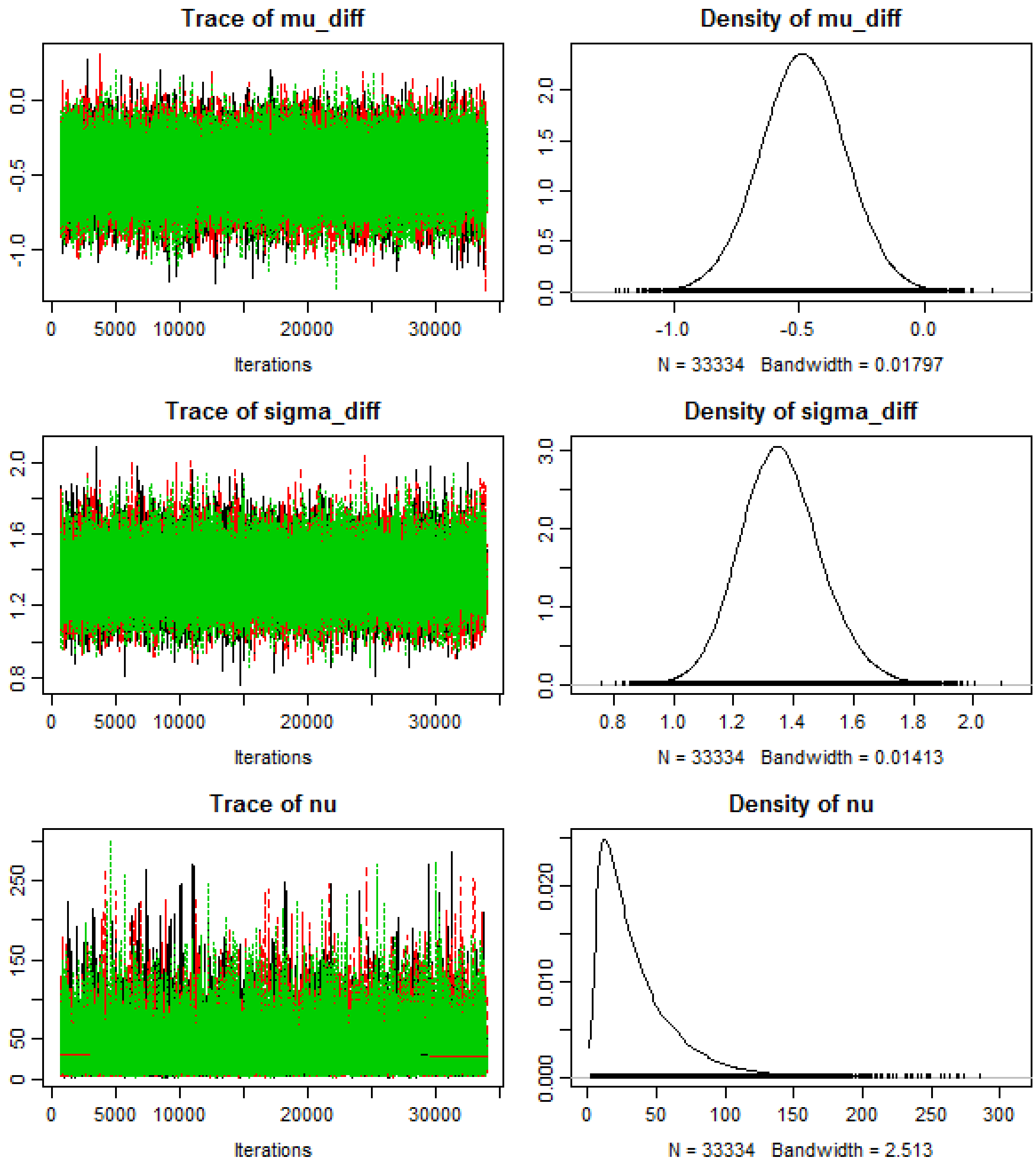


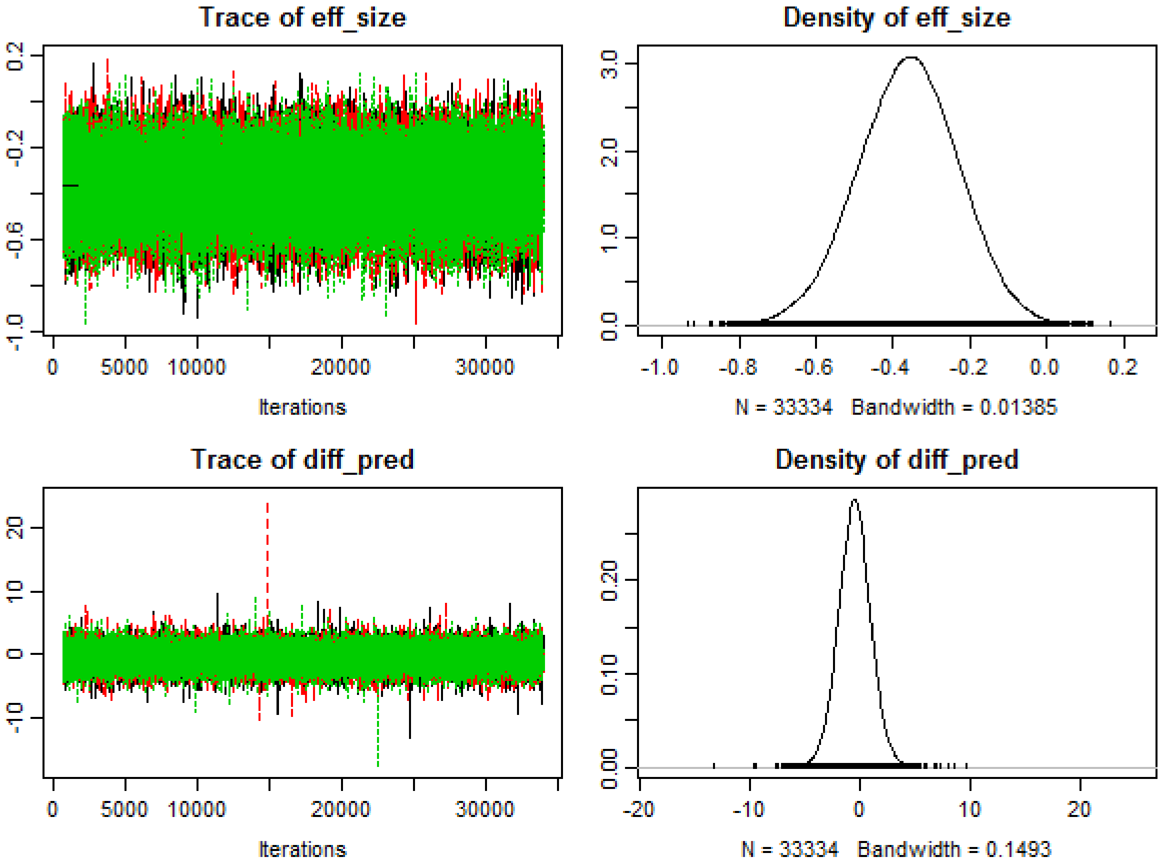

Trace of eff_size
Iterations
Density of eff_size
N = 33334 Bandwidth = 0.01362
Trace of diff_pred
Iterations
Density of diff_pred
N = 33334 Bandwidth = 0.1605

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
             mean     sd mcmc_se n_eff  Rhat
mu_diff    -0.484  0.170   0.001 64751 1.000
sigma_diff  1.359  0.137   0.001 40827 1.000
nu         35.203 29.187   0.219 17750 1.001
eff_size   -0.360  0.131   0.001 60239 1.000
diff_pred  -0.482  1.468   0.005 99761 1.000

mcmc_se: the estimated standard error of the MCMC approximation of the
mean.
n_eff: a crude measure of effective MCMC sample size.
Rhat: the potential scale reduction factor (at convergence, Rhat=1).

  Model parameters and generated quantities
mu_diff: the mean pairwise difference between dataexp2$v10 and dataexp
2$v11
sigma_diff: the scale of the pairwise difference, a consistent
  estimate of SD when nu is large.
nu: the degrees-of-freedom for the t distribution fitted to the pairwi
se difference
eff_size: the effect size calculated as (mu_diff - 0) / sigma_diff
diff_pred: predicted distribution for a new datapoint generated
  as the pairwise difference between dataexp2$v10 and dataexp2$v11
```

```
Quantiles
             q2.5%   q25% median   q75%  q97.5%
mu_diff      0.167  0.402  0.523  0.646   0.885
sigma_diff   1.204  1.369  1.459  1.556   1.765
nu           5.933 16.357 28.903 49.607 116.042
eff_size     0.111  0.274  0.360  0.447   0.615
diff_pred   -2.596 -0.489  0.529  1.540   3.647
```

V_{10} vs. V_{11}


Trace of mu_diff
Iterations
Density of mu_diff
N = 33334 Bandwidth = 0.01797
Trace of sigma_diff
Iterations
Density of sigma_diff
N = 33334 Bandwidth = 0.01413
Trace of nu
Iterations
Density of nu
N = 33334 Bandwidth = 2.513


Trace of eff_size
Density of eff_size
Iterations
N = 33334 Bandwidth = 0.01385
Trace of diff_pred
Density of diff_pred
Iterations
N = 33334 Bandwidth = 0.1493

```
Iterations = 601:33934
Thinning interval = 1
Number of chains = 3
Sample size per chain = 33334

  Diagnostic measures
             mean     sd mcmc_se  n_eff  Rhat
mu_diff     0.524  0.182   0.001  65510 1.000
sigma_diff  1.466  0.143   0.001  45218 1.000
nu         37.497 29.840   0.214  19470 1.001
eff_size    0.361  0.129   0.001  65616 1.000
diff_pred   0.529  1.571   0.005 100633 1.000

mcmc_se: the estimated standard error of the MCMC approximation of the
mean.
n_eff: a crude measure of effective MCMC sample size.
Rhat: the potential scale reduction factor (at convergence, Rhat=1).
```

```
  Quantiles
            q2.5%   q25% median   q75%  q97.5%
mu_diff    -0.821 -0.597 -0.484 -0.370  -0.152
sigma_diff  1.104  1.267  1.354  1.445   1.644
nu          5.267 14.731 26.577 46.496 112.993
eff_size   -0.621 -0.447 -0.358 -0.271  -0.108
diff_pred  -3.360 -1.432 -0.482  0.455   2.426
```

Appendix F Discussion

Appendix F1 Extrapolation of methodological/statistical future trends based on large data corpora

Bayesian Markov chain Monte Carlo sampling has gained in popularity. However, it has been argued that the relationship between Bayesian methods and various bootstrapping approaches is poorly understood, despite the growing use of posterior probabilities. Moreover, simulation studies in the field of phylogenetics indicate that their results do not always converge (Clyde & Lee, 2001).

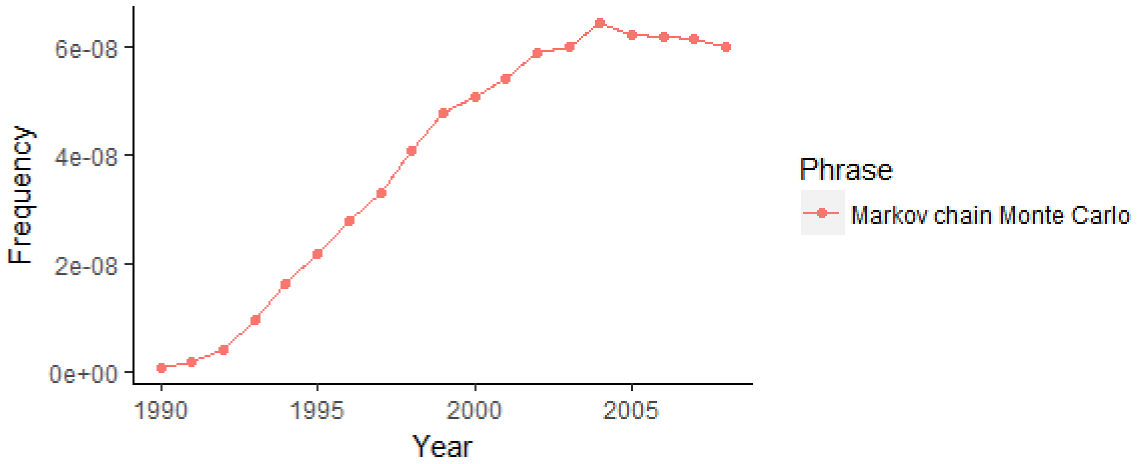


Figure 137. Graph indicating the increasing popularity of MCMC methods since 1990. Data was extracted from the Google Books Ngram Corpus (Lin et al., 2012) with the R package "`ngramr`".[264]

Based on their aggregated data, Google developed a program to successfully predict and "nowcast" the outbreak of flu (https://www.google.org/flutrends) by using a linear model to compute the log-odds for the outbreak of various influenza-type viruses. GoogleTrends is also a powerful tool to investigate the evolution (spreading, fitness) of

[264] URL: https://cran.r-project.org/src/contrib/Archive/ngramr/

memes. The (big) data is publicly available and can be freely downloaded from the Google servers. We argue that GoogleTrends is not only useful to make predictions about economics (Choi & Varian, 2012; Preis, Moat, & Eugene Stanley, 2013), disease outbreaks (i.e., epidemiological research) (Carneiro & Mylonakis, 2009; Nuti et al., 2014), house prices (Wu & Brynjolfsson, 2009), claims for unemployment benefits (Choi & Varian, 2009), developments in engineering (Rech, 2007), and liquidity in German stocks (Bank, Larch, & Peter, 2011), to name just the most salient query categories. It can also be utilised to extrapolate and forecast trends about the usage and popularity (memetic evolution) of statistical and analytical methods. We compared various statistical methods on the basis of dataset provided by Google. For this purpose, we utilised the R package "`gtrendsR`"[265] in order to download and analyse the data. We plotted the trends for various countries (using ISO3166-2 country codes), viz., we visualised interest as a function *f* of time *t* (see Figure 138). A zoomable vector graphic for closer visual inspection can be downloaded as a PDF from the following URL: http://irrational-decisions.com/phd-thesis/gtrends-mcmc.pdf. The underlying dataset is also available as a raw *.txt file: http://irrational-decisions.com/phd-thesis/gtrends-mcmc.txt.

[265] The code is available on the GitHub repository: https://github.com/PMassicotte/gtrendsR (the package also allows to analyse and forecast trends for Google image searches and YouTube, Froogle, and Google News, *inter alia*).

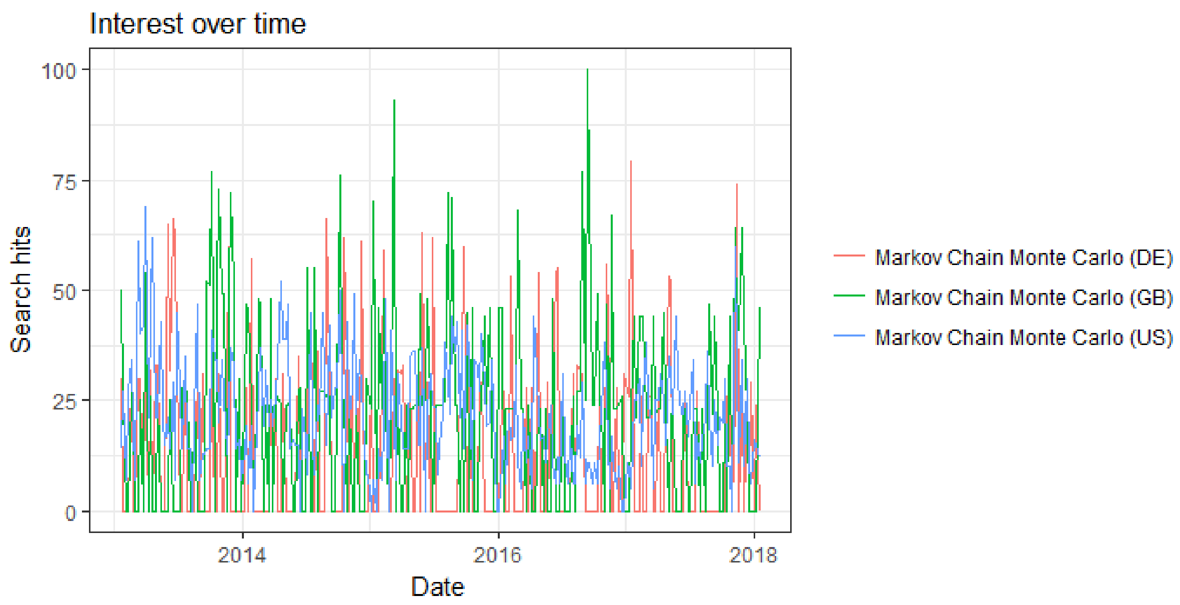


Figure 138. Discrete time series for the hypertext web search query "Markov chain Monte Carlo" since the beginning of GoogleTrends in 2013/2014 for various countries (DE=Germany, GB=Great Britain, US=United States).

Figure 139. Color-coded geographical map for the query "Markov chain Monte Carlo" (interest by region).

If desired, the "`gtrendR`" package allows for much finer grained geographical analysis (e.g., one can specifically focus on predefined cities).

Annex 1
N,N-Dimethyltryptamine: An endogenous neurotransmitter with extraordinary effects.

Introduction

What is mind? No matter.

What is matter? Never mind.

--George Berkeley (1685-1753)

In this classic couplet, Bishop Berkeley concisely addressed the quintessential philosophical question concerning the fundamental relationship between mind and matter (note that he employs Cartesian dualistic terminology; i.e., *res extensa* vs. *res cogitans*).

The question Berkley poses is the following: Can mind/consciousness ultimately be explained in a purely materialistic framework (is "it" reducible to neurobiological mechanisms, molecules, atoms, etc. pp.)? Vice versa, the quote addresses the inverse question: Can the totality of physical reality (in Lockeian nomenclature, the entirety of "primary and secondary qualities") be accounted for solely in terms of mind? In other terms, is the material world an idealistic creation of the mind, as many ancient eastern metaphysical wisdom traditions postulate (experience, then, is the sole reality and the observer/subject and the observed/object are of identical nature; e.g., Bhagavad Gītā, Vedānta, Rigvedas, Yoga Sūtras of Patañjali)? This paradoxical conundrum is a deep-rooted perennial problem in the philosophy of mind and it has recently become a topic of interest for many neuroscientists.

Neurochemistry of cognition

Contemporary materialistic reductionist neuroscience emanates from the provisional working hypothesis that the underpinnings of human cognition, perception, and consciousness are electrochemical. That is, electrical action potentials and chemical neurotransmission are hypothesized to ontologically cause these phenomena. However, it is possible that this unproven assumption might eventually turn out to be a case of epistemological naiveté.

Nevertheless, it is an established scientific fact that there are certain classes of material substances that affect consciousness reliably (the terms consciousness and mind are consequently used synonymously). However, not any arbitrary substance can alter the mind. The mind-altering substances in question have precisely defined molecular structures, which in turn cause very specific effects. For instance, there are certain psychoactive substances that induce sedation (for instance, Diazepam). This particular sedative is a specific case of a much larger chemical class (i.e., the Benzodiazepine family). Thus, there appears to be a systematic correlation between the chemical structure of certain compounds and the psychological effects they induce (in psychopharmacology this is known as the structure-activity relationship).

Interestingly, especially from a neurochemistry/biology point of view, several naturally occurring secondary (possibly semiotic) plant compounds have close structural relationships with various mammalian (including human) neurotransmitters and can consequently bind to specific cell membrane receptors in the brain. Thereby, these chemicals can reliably change a variety of cognitive and perceptual processes (both quantitatively and qualitatively). N,N-Dimethyltryptamine (abbreviated as DMT) is a prototypical exemplar of such psychoactive chemicals (DMT has been oxymoronically referred to as “the spirit molecule”; but see Strassman, 2001). The receptor binding affinity of DMT is complex and hitherto only partially understood. However, it has been firmly established that DMT non-selectively agonises several members of the 5-HT_2 (5-hydroxytryptamin also known as Serotonin) receptor family (especially the 5-HT_{2A} and 5-HT_{2B} receptor appear to be crucial for its psychoactive effects; but see McKenna et al., 1990; Aghajanian & Marek, 1999; Keiser et al., 2009). Except for the 5-HT_3 receptor, all 5-HT receptors achieve transmembrane signal transduction via the G-protein-coupled receptors. Recently, important fundamental research on the G protein-coupled receptor led to a series of Nobel Prizes (e.g., in 2000, 2004, and 2012). Moreover, it has recently been demonstrated that DMT is an endogenous σ_1 receptor regulator (Fontanilla et al., 2009;) and it has been hypothesized that it plays a mediative role in tissue protection, regeneration, and immunity (Frecska et al., 2013). From a chemical point of view, DMT is a prototypical representative member of the indolealkylamine family known as tryptamines. In its pure form, DMT is a white/clear, pungent-smelling, crystalline solid. Its molecular structural geometry visualized in Figure 140 is closely related to Serotonin.

Figure 140. Chemical structures of Serotonin, Psilocin, and N,N-Dimethyltryptamine in comparison.

Compounds such as psilocin (synonymous with 4-hydroxy-N,N-dimethyltryptamine, a precursor of psilocybin which is also known as O-phosphoryl-4-hydroxy-N,N-dimethyltryptamine) and DMT (N,N-Dimethyltryptamine) have chemical structures that resemble the neurotransmitter serotonin (5-hydroxytryptamine). This structural similarity to serotonin allows them to stimulate serotonin-sensitive neurons. Note that the intermolecular serotonin motif is embedded in both structures.

From a phylogenetic perspective, DMT is an evolutionary very old molecule which is ubiquitously present in the plant and animal kingdom (Smith, 1977). In 1961, Nobel Prize laureate Julius Axelrod reported in the journal Science that the enzyme N-methyltransferase in a rabbit's lung is able to mediate the biotransformation of tryptamine into DMT (Axelrod, 1961). More recent converging evidence strongly suggests that DMT is an endogenous neurotransmitter in the human brain (e.g., Cozzi, et al., 2011; Fontanilla, et al., 2009; Cozzi, et al., 2009). Surprisingly, DMT is *actively* transported into the brain via the blood-brain-barrier (a process that is costly in energetic terms because it requires movement against the concentration gradient). This factum has been discovered by Japanese scientists 30 years ago (i.e., Yanai et al., 1986). Given that the brain in an extremely sensitive homeostatic organ, it constantly protects itself from toxins and undesired agents. Consequently, the blood-brain-barrier is highly selective and only very few essential compounds like glucose and other essential nutrients are actively moved across this membrane into the brains tissue. The phenomenon that DMT is actively transported across this protective barrier suggests that it plays a crucial role in ordinary brain metabolism. Moreover, DMT does not built up tolerance, as other psychoactive tryptamines do (no significant desensitisation after repeated administration; see Strassman & Qualls, 1994; Strassman et al., 1994) and it is quickly metabolised (consequently its duration of action is relatively short-lived) . Again, this indicates that it is a natural building block of mammalian neurochemistry. At the moment, there is no explanation as to why mammals have evolved an endogenous neurotransmitter that is able to produce profoundly altered states of consciousness. From an evolutionary point of view one has to ask the question: What is the adaptive advantage of this compound in terms of survival or reproduction? However, given that the intracellular cascade triggered by DMT is not yet fully understood it seems very difficult to imagine that science is soon able to account for its much more intricate effects on perception and consciousness (the hard problem) from a quantitative point of view.

DMTs qualitative phenomenology

From a psychological vantage point, DMT has very remarkable effects, too. One of DMTs most salient activity characteristics is that it affects visual perception in the most spectacular ways possibly imaginable. In addition, it profoundly changes the functioning of a multitude of core cognitive capacities. A brief (though incomplete) synopsis of DMTs subjective effects is summarised in the following list:

- Profound changes in sensory perception across modalities (e.g., perceptual distortions, vivid cross-modal hallucinations, visions, synaesthesia)
- Highly symmetric and oftentimes fractal multidimensional visual hallucinations of astonishing beauty and complexity
- Spectacular visual percepts (impossible objects which are essentially ineffable)
- Subjective experience of extrasensory perceptions (e.g., telepathic phenomena are commonly reported)

- Changes in time and space perception (e.g., time dilation, timelessness/experience of infinity/eternity, limitlessness/omnipresence)
- Journey-like “breakthrough into hyperspace” (trans-dimensional travel into parallel dimension and contact with conscious “otherworldly humanoid beings” is commonly reported under high doses of DMT)
- Altered body image (e.g., out-of-body-experience, taking on an animal/alien body)
- Intense changes in mood (ranging across the whole spectrum of emotions from total serenity/bliss to extreme terror)
- Sense of profound meaning and deep spiritual insights (e.g., gnosis)
- Experience of very profound “mystical states”
- Dissolution of ego boundaries (e.g., ego-death, shared consciousness)
- Feelings of interconnectedness (e.g., communion with nature, monistic all-is-one experience)
- State of union and spontaneous realisation of oneness (nonduality, yoga)
- Near-death experience
- Experience of emptiness, nothingness, pure I-am-ness
- Feelings of tranquillity
- Being freed from one’s body and becoming integrated with one’s cosmic nature
- Feeling of sudden realisation of one’s homogenous cosmic essence
- State of inner harmony (Samādhi)
- Experience of a transcendental reality
- Collapse of ego-ignorance phantom (dissolution of self-limitation)
- Transformation of self-perception, transmutation of entire being (self-transcendence)
- Expansion of awareness (experience of boundless primordial awareness)

- Experience of higher states of consciousness
- Feelings of awe and wonder
- Feeling of awakening from an illusion to a larger “more real” reality
- Appreciation of nature (perception of nature as animated and alive, biophilia)
- Sudden insights into the nature of self and the nature of reality (epiphany or “satori” like experience - seeing into one's true nature)
- Access to unconscious “Jungian alchemical archetypal” information

<u>Potential adverse effects</u>

- Acute panic reaction (depending on idiosyncratic personality structure and situation)
- Substance induced psychosis (ICD-10 diagnosis code F16.5 – low incidence rate)
- Hallucinogen persisting perception disorder (DSM-IV diagnosis code 292.89 – low incidence rate)

The following paragraphs reprint two experiences reported by research subjects who participated in Rick Strassmans early DMT which were conducted in Mexico in the 1990s.

“*The trip started with an electric tingling in my body, and quickly the visual hallucinations arrived. Then I noticed five or six figures walking rapidly alongside me. They felt like helpers, fellow travelers. A humanoid male figure turned toward me, threw his right arm up toward the patchwork of bright colors, and asked, "How about this?" The kaleidoscopic patterns immediately became brighter and moved more rapidly. A second and then a third asked and did the same thing. At that point, I decided to go further, deeper. I immediately saw a bright yellow-white light directly in front of me. I chose to open to it. I was consumed by it and became part of it. There were no distinctions—no figures or lines, shadows or outlines. There was no body or anything* *inside or outside. I was devoid of self, of thought, of time, of space, of a sense of separateness or ego, or of anything but the white light. There are no symbols in my language that can begin to describe that sense of pure being, oneness, and ecstasy. There was a great sense of stillness and ecstasy.*" (excerpt taken from Strassman, 2001; p.244)

"Eight minutes into his non-blind high-dose injection, he described this encounter: *That was real strange. There were a lot of elves. They were prankish, ornery, maybe four of them appeared at the side of a stretch of interstate highway I travel regularly. They commanded the scene, it was their terrain! They were about my height. They held up placards, showing me these incredibly beautiful, complex, swirling geometric scenes in them. One of them made it impossible for me to move. There was no issue of control; they were totally in control. They wanted me to look! I heard a giggling sound - the elves laughing or talking at high-speed volume, chattering, twittering.*" (excerpt taken from Strassman, 2001, p. 188).

It should be noted that the phenomenological experiences reported under the influence of DMT are interindividually very heterogeneous (perhaps partially due to a combination of genetically coded neurotransmitter receptor polymorphisms and idiosyncratic psychological variables) and are contingent upon set and setting (that is, internal psychological and external situational factors play an important role). However, several phenomenologies are reliably induced across diverse subjects (e.g., complex visual hallucinations, out-of-body-experiences, trans-dimensional travels, etc.).

Space does not permit a detailed discussion of DMTs experiential phenomenology, particularly because linguistic expressions are circuitous and often largely inadequate in order to convey its diverse spectrum of psychological effects (ineffability is a defining hallmark of the translinguistic DMT ontology which reaches far beyond the bounds of human imagination). The perceptions and insights that are catalysed by this compound are often described as being at total invariance with the socially grounded models of contemporary western paradigms. Interestingly, several of DMTs structural analogues (e.g., Psilocybin, a compound which is present in the "magic" mushrooms which are endemic to the UK, Mantle & Waight, 1969; see also Figure 1) have phenomenologically comparable though not identical effects (cf. Hasler et al., 2004). However, hitherto the extraordinary cognitive changes triggered by DMT cannot be accounted for by any of the existing theoretical frameworks provided by neuroscience and psychology.

Endogenous but prohibited

Despite the exceptional characteristics of DMT and its ubiquity in nature, many mainstream psychologists and even professional neuroscientists are utterly unaware of its existence (presumably, due to academic overspecialisation and the fact that the conventional neuroscience textbooks do not mention it at all, e.g., Gazzaniga & Mangun, 2014; Kolb & Whishaw, 2009). Furthermore, systematic and methodologically valid research is highly restricted due to the fact that DMT is classified as a "Class A drug" in the UK and similarly tightly regulated as a "Schedule I substance" in the US. This classification is clearly not evidence based and it inhibits scientific progress and innovation (let alone the fact that it violates the principle of cognitive liberty, that is, the right to mental self-determination).

In this context, it is noteworthy that the Brazilian União do Vegetal (UDV - www.udv.org.br) was granted precedential legal permission to use a DMT containing drink (named Ayahuasca) in their ceremonies. The UDV, which is claiming roots as far back as the 10^{th} century BC, utilises Ayahuasca in a program of spiritual evolution based on mental concentration and the search for self-knowledge. From a juridical point of view, it is very interesting that the US Supreme Court adjudicated in 2006 that the UDV is legally permitted to deploy Ayahuasca as a religious sacrament (under the protection of the "Religious Freedom Restoration Act").

Ayahuasca: An ancient phytochemical synergy

From a much larger historical perspective, DMT has been utilized for spiritual/shamanistic rituals for millennia by several ancient cultural traditions. As mentioned before, it constitutes the active pharmacological principle in Ayahuasca, a plant based, drinkable concoction, which is traditionally used by indigenous tribes in the Amazonian rainforest for divinatory and healing purposes. In itself, DMT is orally inactive because the monoamine oxidase (MAO) system within the gastro-intestinal (GI) tract deaminates it. However, somehow the aboriginals have developed sophisticated intuitive knowledge concerning its combinatorial pharmacodynamics. In order to prevent DMTs decomposition in the gut, they mix it with a plant-based MAO inhibitor.

To be specific, the typical primary ingredients of the Ayahuasca brew consist of two plants, Psychotria Viridis (which contains the DMT) and Banisteriopsis Caapi (which contains the β-carboline harmala alkaloid designated as harmine). Harmine functions as a selective and reversible inhibitors of the enzyme monoamine oxidase A (MAO-A) that prevents the enzymatic breakdown of DMT in the GI-tract, thereby allowing it to be transported via the blood-brain barrier. Hence, it is the combination of these two plants, which enables DMT to become psychoactive. Quite thought-provokingly, the chemical literature labelled Harmine for some time as telepathine. This chemical was so named because of the effects reported by Amazonian tribal members (e.g., telepathic communication, clairvoyance, precognition, psychic diagnosis, necromancy).

Western science has just relatively recently learned about DMT and its psychoactive effects from ethnophamacologists who were able to conserve this ancient cultural knowledge literally in the last minute because old shamanic traditions are being extinguished at a fast pace by the modern industrial world. The inhabitants of the Amazonian rainforest have a very close relationship with, what they call “plant-spirits”. They regard Ayahuasca as a wise “plant teacher” which enables them to communicate with the “spirit world” (Beyer, 2009). It should be noted that in the shamanic paradigm the dichotomy between spiritual and medicinal is not clear-cut as the European heritage suggests and “sacred” plants play a central role in these traditional indigenous contexts.

Unfortunately, the Amazonian rainforests are currently being destroyed at a very alarming rate. The Amazonian biodiversity is among the richest in the world, although the number of species in the red list of the IUCN (International Union for Conservation of Nature) is growing steadily every year. The destruction of the natural environment goes hand in hand with the loss of culturally embedded ancient folk-knowledge concerning the utilisation of specific plants for medicinal and spiritual purposes. Moreover, younger generations are not very interested in the continuation of the Shamanic traditions of their predecessors. They prefer to move into modern technologized cities in order to take their place in the materialistic market economy and consequently thousands of years of accumulated and potentially highly valuable information is lost in this cultural transition.

Conclusion

Brevity does not permit me to review many intriguing aspects of this multifaceted topic (e.g., DMTs relation to psychological conditioning/extinction, neurogenesis, neuroplasticity, psychoneuroindocrinology, psychoimmunology, epigenetics, and the neuroanatomical correlates of its effects). I could only try to provide a very rudimentary introduction to this fascinating newly emerging research domain. It should be emphasized that this subject (psychoactive plant compounds and human cognition, perception, and consciousness) is located at the cutting edge of modern cognitive neuroscience and psychology and it encompasses many other adjacent disciplines (e.g., physics, chemistry, botany, pharmacology, psychiatry, anthropology, history, archaeology, philosophy, religion, medicine, art, law, ethics, etc. pp.; cf. Bois-Mariage, 2002).). I am convinced that many researchers will develop a deep interest for this topic if they have not already done so.

For further information, the interested reader is referred to the book "DMT: The spirit molecule" by Rick Strassman (2001) who was the first to conduct FDA approved rigorous scientific human trials with DMT in the 1990s. His book provides a comprehensive synopsis of DMTs neurochemistry and its experiential phenomenology. Strassman hypothesized back in the 90s that DMT might be present in the human pineal gland. This hypothesis was largely ignored by the scientific community. However, his prediction has recently been partially corroborated. In 2013, researchers first reported the presence of DMT in rodent pineal gland microdialysate (Barker, et al., 2013). The pineal is a photoreceptive endocrine gland whose primarily known function is the regulation of the circadian rhythm via the secretion of melatonin (N-acetyl-5-methoxy tryptamine), another serotonergic member of the tryptamine family (but see Reiter, 1991). Because the photosensitive pinealocytes have a strong resemblance to the photoreceptor cells of the eye, the pineal gland has also been labelled as the "third parietal eye" (Eakin, 1973). It has been subject to much speculation since Claudius Galenus and later René Descartes who famously termed it the "principal seat of the soul".

Future research directions

To conclude, I would like to delineate some potentially fruitful directions for future research on DMT and formulate several empirically testable hypotheses:

DMT and its vastly more potent relatives (e.g., 5-methoxy-N,N-dimethyltryptamine acronymized as 5-Meo-DMT) might lead to the discovery of new classes of neurotransmitter systems (cf. the discovery of the endocannabinoid system) that would deepen our understanding of basic neurochemistry and may ultimately lead to the design of new pharmacological agents in order to treat mental pathologies (cf. Jacob & Presti, 2005) or to enhance cognition (e.g., nootropics) or expand consciousness in the healthy population.

Another research agenda should focus the role of DMT and its relatives in molecular biology. The National Genome Research Institute published data that indicates that the costs of genetic sequencing (DNA micro arrays) are decreasing fast than Moore's law for computational performance predicts (http://genome.gov/sequencingcosts). This development opens up unprecedented large-scale analytic possibilities for the newly emerging discipline of neurogenetics. For example, in analogy to the genome, the proteome, and the connectome, the receptorome aims to map the total number of genes that code for receptors and receptor molecules in the brain. In this regard, it has recently been argued in a paper titled "Psychedelics and the Human Receptorome" that "it should be possible to use this diverse set of drugs (psychedelics) as probes into the roles played by the various receptor systems in the human mind" (Ray, 2010, p.1; content in bracket added).

The neurochemical correlates of the various meditative states of mind are another vibrant research topic. Researchers have observed statistically significant overlap between the neural correlates of mediation and psychedelic experiences. Consequently, there might be a significant degree of overlap between the neurochemical substrates of these altered states of mind. In this regards, the influence of DMT on microtubule (neuronal microstructures which form part of the cytoskeleton) should be a focal point of systematic scrutiny (but see Hameroff & Penrose, 2014).

Recent research provides evidence that DMT has psychoneuroendocrinological and psychoneuroimmunological effects (Frecska et al., 2023). Fascinatingly, it has been shown in a publication by Epel et al. in 2009 (co-authored by Nobel Prize laureate Elizabeth Blackburn) that mediation influences telomere length (an indicator of biological age). Given that DMT and various related psychoactive tryptaminergic compounds induce states of mind that are partially qualitatively congruent with the mental states achieved by meditative practices it seems likely that the experiences triggered by DMT also have the potential to positively affect telomere length (e.g., via telomerase activity). Based on the assumption that DMT can induce robust longitudinal changes on various levels (physical and psychological) it seems likely that genetic changes are involved. Future research should focus on the (epi)genetic fundament of these changes (how gene methylation/transcription/ expression is altered following exposure to psychoactive substances).

Another line of research should investigate the interplay between quantum physical phenomena and altered states of consciousness. The theoretical framework of quantum physics ascribes a pivotal role to consciousness (e.g., Schrödinger's wave equation). Consequently, substances which profoundly change the main pillar of this theoretical tenet (that is, consciousness and the associated mechanics of perception) should be of significant interest to the physics community. The disciplines of physics and psychology should pursue a close interdisciplinary discourse and collaborations in order to combine their efforts and insights (this has happened before, for instance, the physicists Albert Einstein and Wolfgang Pauli were in close communication with depth-psychologist C.G. Jung).

Yet another auspicious line of research is an investigation of the effects of DMT on creative thinking and cognitive flexibility (i.e., DMT as a catalyst for creativity and innovation; cf. Frecska et al., 2012). Given that DMTs phenomenology deconstructs conventional orthodox cultural worldviews it has the potential to facilitate novel perspectives on multifarious philosophical questions and might even contribute to the resolution of “hard” scientific problems (cf. Willis, et al., 1966).

There is much more scientific virgin soil that awaits thorough investigation. A largely unexploited research area comprises of careful empirical tracings of the effects of various non-naturally occurring synthetic psychoactive tryptamines which have been developed by the pioneering chemist Alexander Shulgin (see Shulgin & Shulgin, 1997). His work entails an extensive chemical toolbox for future work in neuroscience and psychology. In his book “TiHKAL - Tryptamines I have known and loved” he provides a detailed index of more than 50 psychedelic compounds (many developed by himself). The book entails a description of their synthesis, exact chemical structures, dosage recommendations, and qualitative comments. Most of these compounds have yet to be rigorously researched – a task for the next generation of curious and open-minded scientists. To provide an intriguing example, one of the tryptamines described by

Shulgin is DiPT (Diisopropyltryptamine). It has unique properties because it does almost exclusively affect the auricular sense (i.e., nonlinear shifts in pitch perception - other sensory modalities remain largely unaffected). It is apparent that DiPT should be of keen interest to researchers trying to understand the neural basis of auditory perception. However, up until now systematic research has not been conducted (experimental ornithological studies of avian vocalisation/bioacoustics might be a fertile starting point).

Finally yet importantly, the experiences DMT evokes are of particular fascination to artists, for obviously reasons (e.g., Grey, 2012). Several visionary artists have been deeply inspired by their transcendental experiences with DMT and related compounds (see Figure 2).

Figure has been removed due to Copyright restrictions

Figure 2: The net of being by Alex Grey (inspired by the Mahayanian metaphor of Indra's net).

Further artworks created by Alex Grey are available under the following URL: http://alexgrey.com/art/

Finally, it remains an open question why DMT (and its structural relatives) are not part of the mainstream discourse in psychology and neuroscience. Especially given its apparently central role in perceptual processes, its pertinence for consciousness studies, its implications for understanding mood disorders and emotions in general, and its far-reaching philosophical implications? A Kuhnian paradigm shift is needed. The study of naturally occurring (plant derived) substances should be allowed into academia in order to foster the elucidation of the interplay between psychoactive chemicals, cognition, and consciousness.

Off the Lip: Science over politics!

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Annex 2
5-methoxy-N,N-dimethyltryptamine: An ego-dissolving catalyst of creativity?

Abstract

5-MeO-DMT is an endogenous tryptamine alkaloid with a high, nonselective affinity for various serotonin receptors. It has a unique psychopharmacological profile and its effect cannot be compared to other psychedelics. Despite it wide distribution in nature and long history of human usage, systematic psychological research is currently virtually absent. We argue for the utility of various naturally occurring serotonergic psychoactive compounds as valuable psychological research tools which have the potential to advance our understanding of cognitive and neuronal processes, especially those which underpin various aspects of creativity and aesthetic perception. We postulate that 5-MeO-DMT has great scientific merit in this respect due to its unparalleled ego-dissolving properties. An eclectic interdisciplinary perspective is adopted, and we present ethnographic, historical, qualitative, and quantitative evidence in support of our claim. The article then reviews two pertinent recent empirical experimental studies in more detail: 1) A psychopharmacological study focusing on the role of psilocybin on the Big-5 personality trait "Openness to Experience" and 2) a multimodal fMRI based cognitive neuroscience study which investigates the influence of LSD on neuronal functional connectivity patterns. Based on this empirical and theoretical background, we formulate several novel and experimental falsifiable hypotheses concerning the role of 5-MeO-DMT as a neurochemical catalyst of creativity. Finally, we briefly adumbrate the *de facto* irrational "quasi-Orwellian" nature of the recently ratified "Psychoactive Substances Act" (2016, United Kingdom) which

inhibits systematic scientific research, antagonizes neurodiversity, and presents a juridically unjustifiable violation of the unalienable human right to cognitive liberty (i.e., freedom of thought). The implications of this highly restrictive and non-evidence based legal framework for unbiased systematic scientific research will be discussed from a Jamesian radical empiricism perspective. In line with other creativity researchers (e.g., Puccio, 2017), we argue that creativity plays a crucial role for the seriously endangered survival of the species and that it is therefore of immense importance to foster novel ways of perceiving, thinking, and consequently behaving.

Introduction

The following quotation from Abraham Maslow's book "Towards a psychology of being" provides an apt primer and some grounding for the following discussion:

"*An essential aspect of SA* [Self-Actualized] *creativeness was a special kind of perceptiveness that is exemplified by the child in the fable who saw that the king had no clothes on - this too contradicts the notion of creativity as products. Such people can see the fresh, the raw, the concrete, the ideographic, as well as the generic, the abstract, the rubricized, the categorized and the classified. Consequently, they live far more in the real world of nature than in the verbalized world of concepts, abstractions, expectations, beliefs and stereotypes that most people confuse with the real world. This is well expressed in* [Carl] *Rogers' phrase "openness to experience*" (Maslow, 1968, p. 145, contents in brackets added by the author).

The "single-state fallacy" (T. B. Roberts, 2006, p. 104) pertains to the widely held naïve assumption that worthwhile cognition *exclusively* takes place in "normal" alert waking consciousness. However, there exists copious evidence that important creative ideas can emerge from non-ordinary states of mind (Tart, 1972, 2008). A well-documented illustrative historical example is August Kekulés discovery of the benzene structure in 1858, a landmark in the history of science which heralded the birth of the structural theory of organic chemistry (Kekulé, 1866, 1890). Kekulé had a daydream of the *Ouroboros* (an ancient symbol of a snake seizing its own tail) and this dream-image provided him with the idea of the cyclic structure of benzene (Rocke, 2015). Interestingly, the depth-psychologist C.G. Jung assigned specific archetypal and alchemical significance to this symbol (Jung, 1969).

Jung's mentor, Sigmund Freud, regarded dreams as the royal road to the unconscious (Freud, 1939). However, unbeknownst to Freud, besides dreams and free-association techniques there are other much more effective methods that can make unconscious contents more accessible. Certain neuroactive chemical substances, colloquially termed psychedelics, are particularly productive tools in this regard. There is significant evidence that psychedelics can, *inter alia*, enhance creative ideation (e.g., ideoplasticity)[266] and aesthetic perception.

Numerous self-reports indicate that psychedelics facilitate perspectival multiplicity. In the context of creative problem-solving, it has been suggested that psychedelics can enable the adoption of "multiple viewpoints of a problem" (Sessa, 2008). In other terms, a larger proportion of the entire solution space is simultaneously taken into consideration[267]. Psychedelics have the potential to facilitate the cognitive ability to handle multiple seemingly paradoxical alternatives simultaneously, i.e., their neurochemical effects assist the cogniser to overcome the need for closure and they facilitate the ability to deal with contextual ambiguity and vagueness, concepts which are interestingly of crucial importance in the context of non-Kolmogorovian quantum logic (Blutner et al., 2013; Putnam, 1983). We argue that psychedelics soften the rigidity of habitual cognitive structures, thereby enabling novel and more flexible modes of cognition[268]. For instance, the third Aristotelian law of thought (*tertium non datur*), i.e., the law of the excluded middle (Whitehead & Russell, 1910), can be more

[266] The term "ideagens" has been suggested (T. B. Roberts, 2006).

[267] The underlying cognitive and neural mechanism are hitherto not well-understood but potential functional models involve Baddeley's model of working memory (e.g., visuospatial sketchpad, excecutive functions; Baddeley, 1992). Associated neuroanatomical correlates likely involve prefrontal/cingulate/limbic structures (Della Sala, Gray, Spinnler, & Trivelli, 1998; Kerns et al., 2004; Madarasz et al., 2016). From a neurochemical point of view, the various serotonergic neurotransmitter systems appear to be of central importance (Carhart-Harris & Nutt, 2017; Meneses, 1999; Nichols, 2016).

[268] Experimental research on the effect of various psychedelics on functional fixedness would be potentially fruitful to empirically corroborate this postulate. It has been argued that "innovation relies on the obscure" and that the overcoming functional fixedness is crucial in this respect.

readily transcended and multiple seemingly polar (paradoxical) propositions can be held simultaneously thereby multiplying cognitive degrees of freedom (e.g., in the context of combinatorial/divergent thinking). The quantum physical concept of complementarity appears to be pertinent in this respect[269]. These epistemological aspects of the psychedelic experience might also prove to be of central importance for the psychology of thinking and reasoning (for instance, in the context of Kahneman and Tversky's heuristics and biases research tradition). For instance, psychedelics might help to overcome certain cognitive biases, e.g., self-serving confirmation-biases and syllogistic belief-biases (this hypothesis could be empirically tested in a straightforward experimental design). Furthermore, if utilized correctly, psychedelics can be invaluable neurochemical tools for self-reflection, self-development, self-actualization, and self-transcendence in the Maslowian sense. In his seminal book "Farther Reaches of Human Nature" Maslow articulates a "condensed statement" on the meaning of transcendence: "*Transcendence refers to the very highest and most inclusive or holistic levels of human consciousness, behaving and relating, as ends rather than means, to oneself, to significant others, to human beings in general, to other species, to nature, and to the cosmos*" (Maslow, 1972, p. 269).

Science in now in a position to induce transcendental states of consciousness with a substantial degree of reliability in controlled experimental settings (MacLean et al., 2011). Moreover, Maslow's description of transcendence resonates with a recent finding that mystical experiences occasioned by psilocybin are statistically significantly correlated with increases in altruism (MacLean et al., 2011). Altruism, in turn, appears to be correlated with a reduction of self-centered (i.e., selfless) cognitions. It is apparent

[269] Niels Bohr famously wore the Yin and Yang symbol together with the motto "*Contraria Sunt Complementa*" (opposites are complementary) on his coat of arms coat of arms, thereby illustrating the transcendence of conceptual dichotomies which is a crucial aspect of quantum mechanics (e.g., superposition, complementarity) and arguably of the psychedelic phenomenology.

that psychedelics are important to the field of transcendental psychology which in turn makes unique and fruitful theoretical contributions to research on creativity and aesthetic apperception. Interestingly, recent work cutting-edge work suggests that psilocybin enhances feeling of connectedness (R. Watts et al., 2017) and nature relatedness (Lyons & Carhart-Harris, 2018) in a dose-dependent manner in patients with treatment-resistant depression.

From a pragmatic vantage point on creativity, the crucial importance of psychedelics in the technological development of the personal computer and the internet should be noted. *Prima facie*, this might appear like a hyperbolic statement. However, there is convincing historical evidence in support of the claim that psychedelics played a pivotal role in the highly creative computer-revolution which fundamentally transformed the world we inhabit (see Markoff, 2005; Nelson, 1975). Besides the influence of psychedelics on the development of interconnecting (boundary dissolving) information-technologies like the world-wide-web and the personal computer, innumerable artists[270], especially within the branches of "visionary arts", have been deeply inspired by transcendental experiences elicited by psychedelics (e.g., Grey, 2001). Deep unconscious processes appear to provide impetus and manifest themselves in these highly creative artistic expression (Kandel, 2015). Other more eminent instances that link creativity to psychedelics include, for example, people like Steve Jobs and Nobel laureate Karry Mullis[271]. Jobs famously reported that his experience with Lysergic Acid Diethylamide (LSD) was one of the most important things he did in his life. Karry Mullis was even more explicit in this respect. Mullis was honored for his ground-

[270] Ancient artworks in which psychedelics take a central and honoured place are found in numerous cultures. A representative example is the "Chavín de Huántar" in Peru. Evidence is accumulating that psychedelics played a much more pivotal role in ancient art than most art historian hitherto argued.
[271] It should be emphasized that these chosen examples should not reinforce the superficial conception that creativity only "matters" if it produces material dividends and has no intrinsic value in itself (cf. Flexner, n.d.).

breaking work on the polymerase chain reaction which is still extensively used to replicate DNA fragments. Mullis stated in an interview: "*Back in the 1960s and early '70s I took plenty of LSD. A lot of people were doing that in Berkeley back then. And I found it to be a mind-opening experience. It was certainly much more important than any courses I ever took*" (Schoch, 1994). He claimed that his ability to "*get down with the molecules*" was facilitated by LSD (Slattery, 2015). Moreover, he writes in his autobiography "*The concept that there existed chemicals with the ability to transform the mind, to open up new windows of perception, fascinated me.*" (Mullis, 2000, p. 62). Mullis fascination reverberates with the title of Aldous Huxley's classic book "The doors of perception" (Huxley, 1954) in which Huxley details his extraordinary experience with the ancient psychedelic compound mescaline which was administered to him by the British psychiatrist Humphrey Osmond who coined the term psychedelics[272]. Huxley[273], a creative visionary genius who was a repeated nominee for the Nobel Prize in literature, adopted the title for his book from a phrase found in William Blake's 1793 poem "The Marriage of Heaven and Hell". Blake wrote: "*If the doors of perception were cleansed every thing would appear to man as it is, Infinite. For man has closed himself up, till he sees all things thro' narrow chinks of his cavern.*" According to Huxley and Blake, overcoming the self-centered perspective associated with rigid ego-structures enables the percipient to perceive reality from a more impartial perspective. For obvious reasons, transcending perceptual schemata is crucial in the context of creativity. Psychedelic substances are a *casus sui generis* in this regard because they have the unique potential to profoundly change perceptions and reveal

[272] The word psychedelic is etymologically derived from the ancient Greek ψυχή (psukhḗ, "mind, soul, spirit") + δῆλος (dêlos, "manifest, visible"). Hence, an adequate rough translation is "mind manifesting" or "soul revealing".

[273] An interesting historical factoid is that Huxley wrote a note to his wife while on his death and asked her to inject him with 100μg of LSD (IM). He died while under the influence of the consciousness expanding substance.

states of mind that lie far beyond the ordinary state of waking consciousness. Moreover, they possess the ability to catalyze the most "extraordinary" and complex cognitive/perceptual processes (e.g., transcendence of experiential space-time, synesthesia/somaesthesia, spectacular visual hallucinations, intense vivid imaginations, emotional catharsis, access to unconscious/archetypal contents, profound noetic insights, enhanced biophilia, amplified empathy, etc. pp.). In the context at hand, one of their most important qualities is their ability to enable novel perceptions and their potential to induce the process of ego-dissolution, viz., non-dual experiences[274] (J. V. Davis, 2011).

Among experts in the field of psychedelic research, there is general consensus that psychedelics (i.e., consciousness expanding substances) can augment cognitive processes and specifically creativity in profound ways (Sheldrake, McKenna, Abraham, & Abraham, 2001). Some studies from the 1960s (which are by modern research standards unfortunately methodologically confounded) suggest that psychedelics can significantly enhance creativity and scientific problem solving (W. W. Harman, McKim, Mogar, Fadiman, & Stolaroff, 1966).

Due to the legal prohibition of psychedelics in the late 1960s, research on this fascinating topic has been seriously impeded[275]. After this legally enforced involuntary hiatus, we are currently seeing a renaissance, a new rising wave of psychedelic research (Bolstridge, 2013; Sessa, 2012) using modern psychological methodologies and advanced neuroimaging technologies. However, hitherto systematic scientific research

[274] The concept of non-duality is closely related the Indian philosophical system of "Advaita Vedānta" (Sanskrit: अद्वैत वेदान्त, literally, "not-two") which is one of the most ancient spiritual paths to self-realization. Overcoming/dissolving the illusion of the ego or I-ness principle (Ahaṃkāra) plays a crucial role in this tradition.

[275] After initial studies in German concentration camps (e.g., Auschwitz) the CIA developed its own undercover programs (e.g., Project MK-Ultra) in order to test psychedelics compounds on oftentimes naïve populations (prisoners, mental patients,etc.).

which focuses exclusively on the role of psychedelics in creative thinking is still missing. We expect that future research along these lines will be extremely insightful. Research on psychedelics is especially pertinent for our understanding of the neuroscience of creativity because many psychedelics have endogenous counterparts, that is, they are natural building blocks of human physiology/neurochemistry. Many neuroscientists are utterly unaware that the discovery of LSD led to the idea that certain chemicals might play a role in cognitive processes. Today the fact that neurotransmitters influence cognition is taken for granted. Before 1952, serotonin was thought to be a vasoconstrictor (hence the compound lexeme "sero-tonin"). In 1952-53 serotonin (5-hydroxtryptamin, 5-HT) was discovered in the brain by Betty Twarog, Irvine Page, and Sir Henry Gaddum. In 1953, Sir Henry Gaddum took LSD in a self-experiment. Shortly afterward he and his colleague published a paper on the antagonistic effects of LSD on 5-HT (Gaddum & Hameed, 1954). Gaddum conjectured a common site of action between both compounds and theorized that the cognitive effects of LSD result from its action on 5-HT (Amin, Crawford, & Gaddum, 1954). Because he had experienced the effects of LSD first-hand he knew that it produces significant mental changes. Knowing that LSD antagonizes 5-HT, he made the novel theoretical connection for the first time in the documented history of science. That is, Gaddum was the first to postulate that 5-HT might play a role in cognition.

This historical example clearly demonstrates that the systematic study of psychedelic compounds is indispensable if science wants to understand cognitive processes (e.g., creativity) and their neuronal correlates. We agree with other influential creativity researchers that "evidence gleaned from the structure and function of the brain [can] enhance our ability to foster creativity" (Vartanian, 2013, p. 257; content in brackets added). The systematic investigation of compounds like 5-MeO-DMT might lead to novel psychopharmacological interventions and aid in the elucidation of hitherto unidentified neurotransmitter systems (e.g., N,N-dimethyltryptamine regulates the σ1 “orphan” receptor; Fontanilla et al., 2009).

We will now discuss two more recent experimental studies which are relevant to the psychology and neuroscience of creativity. Based on the literature (e.g., Nour, Evans, Nutt, & Carhart-Harris, 2016), we argue that an understanding of the processes which undergird ego-dissolution is pivotal for advances in our understanding of creativity. In addition, we will briefly discuss the underappreciated and almost unresearched endogenously occurring psychedelic 5-MeO-DMT. We propose that this specific compound is particularly intriguing in the context of ego-dissolution and creativity.

Psilocybin increases “Openness to Experience”

Psilocybin (O-phosphoryl-4-hydroxy-N,N-dimethyltryptamine) is an indole alkaloid which was synthesized and named by the Swiss chemist Albert Hofmann[276] (Hofmann et al., 1959; 1958). The compound is present in more than 150 fungi species, some of which are endemic to the UK (e.g., *Psilocybe semilanceata*, known as Liberty Cap). In shamanic contexts, psilocybin has been utilized for spiritual and healing purposes for millennia[277]. Its molecular structure closely resembles 5-HT. In humans, psilocybin is rapidly dephosphorylated to psilocin (4-N,N-dimethyltryptamine) which functions as a non-selective partial 5-HT receptor agonist (it shows particularly high binding affinity for the 5-HT_{1A} and 5-HT_{2A} receptor subtypes; Nichols, 2004). A landmark study

[276] Hofmann (1906–2008) also discovered LSD in 1938 but he was unaware of its psychoactivity until 1943 when he conducted the first self-experiment. Hofmann, who later served as a member of the Nobel Prize Committee, stated on his 100th birthday: “*It gave me an inner joy, an open mindedness, a gratefulness, open eyes and an internal sensitivity for the miracles of creation.* [...] *I think that in human evolution it has never been as necessary to have this substance LSD. It is just a tool to turn us into what we are supposed to be*.”

conducted at Johns Hopkins University by MacLean, Johnson, & Griffiths (2011) experimentally demonstrated that a single high-dose of psilocybin can induce long-lasting personality changes in the domain "Openness to Experience", as measured by the widely used NEO-PI (Personality Inventory). Openness to Experience (OTE) is one of the core dimensions of the extensively employed quinquepartite (big five) model of personality. OTE is an amalgamation of several interconnected personality traits which include: 1) aesthetic appreciation and sensitivity, 2) fantasy and imagination, 3) awareness of feelings in self and others, and 5) intellectual engagement. Most relevant for the context at hand is the fact that OTE has a strong and reliable correlation with creativity (Ivcevic & Brackett, 2015; S. B. Kaufman et al., 2016; Silvia et al., 2009)[278]. Individuals with high scores on the OTE dimension are "permeable to new ideas and experiences" and "motivated to enlarge their experience into novel territory" (DeYoung et al., 2005). The experimentally induced increase in OTE was mediated by the intensity of the mystical experience occasioned by psilocybin. Importantly, ego-dissolution is a central feature of mystical experiences (see also Griffiths et al., 2006). Hence, it is logically reasonable to assume that the experience of ego-dissolution correlates significantly with an increase in OTE.

LSD selectively expands global connectivity in the brain

A recent study conducted by Tagliazucchi et al. (2016) conducted at Imperial College London administered LSD intravenously to healthy volunteers. The researchers found that LSD-induced ego-dissolution was statistically significantly correlated with an

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[278] For instance, the Pearson correlation coefficient for "global creativity" and OTE is .655 and for "creative achievement" .481, By contrast, "Math–science creativity" is not statistically significantly correlated with OTE ($r = .059$; ns; for further correlation between various facets of creativity and the Big Five factors see Silvia, Nusbaum, Berg, Martin, & O'Connor, 2009). The salient correlation between OTE and creativity has been reported in many studies (a pertinent meta-analysis has been conducted by Feist, 1998; a recent study reporting a strong relationship between OTE and creativity has been conducted by Puryear, Kettler, & Rinn, 2017). Furthermore, a meta-analytical structural equation model of 25 independent studies showed that OTE is the strongest FFM predictor of creative self-beliefs ($r = .467$; Karwowski & Lebuda, 2016).

increase in global functional connectivity density (FCD) between various brain networks (as measured by fMRI). As discussed in the previous study by MacLean et al. (2011), mystical experience is correlated with an increase in OTE which in turn is strongly correlated with creativity.

One of the key findings of the current fMRI-study was that high-level cortical regions and the thalamus displayed increased connectivity under the acute influence of LSD. To be specific, increased global activity was observed bilaterally in the high-level association cortices and the thalamus (often regarded as the brains "central information hub" which relays information between various subcortical areas and the cerebral cortices). The global activity increase in the higher-level areas partially overlapped with the default-mode, salience, and frontoparietal attention networks (see Figure 141). The FCD changes in the default-mode and salience network were predicted a priori due their association with self-consciousness. As predicted, a significant correlation between subjective ego-dissolution and activity changes in these networks was detected. That is, the increase in global connectivity was significantly correlated with self-report measures of ego-dissolution.

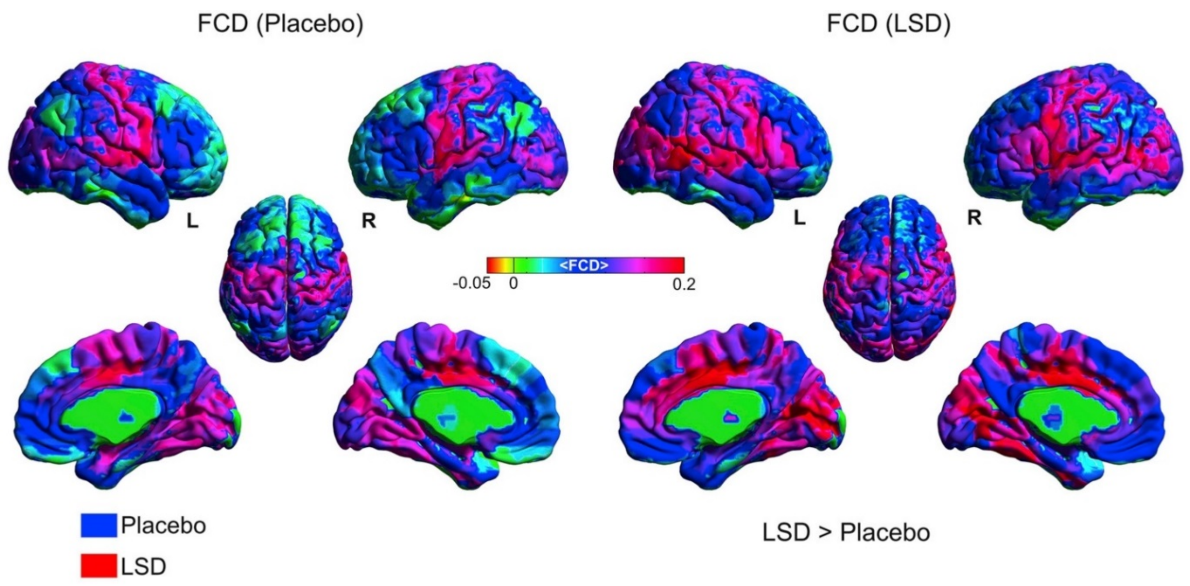

Figure 141. Average functional connectivity density Φ under LSD vs. control condition (adapted from Tagliazucchi et al., 2016, p. 1044)

The results demonstrate for the first time that LSD increases global inter-module connectivity while at the same time decreasing the integrity of individual modules. The observed changes in activity significantly correlated with the anatomical distribution of 5-HT_{2A} receptors. Interestingly, LSD enhanced the connectivity between normally separated brain networks (as quantified by the widely used Φ connectivity index[279]). This result is especially relevant for researchers who want to identify the neural correlates of creativity because an enhanced communication between previously disconnected neuronal network modules is assumed to be crucial for the generation of novel percepts and ideas (e.g., D. W. Moore et al., 2009). The authors concluded that LSD reorganizes the rich-club architecture of brain networks and that this restructuring is accompanied by a shift of the boundaries between self and environment. That is, the

[279] The rich-club coefficient Φ is a networks metric which quantifies the degree to which well-connected nodes (beyond a certain richness metric) also connect to each other. Hence, the rich-club coefficient can be regarded as a notation which quantifies a certain type of associativity.

ego-based dichotomy between self and other, subject and object, internal and external, dissolves as a function of specific connectivity changes in the modular networks of the brain[280].

Taken together, Tagliazucchi et al. (2016) demonstrate that LSD induced ego-dissolution is accompanied by significant changes in the neuronal rich-club architecture and that ego-dissolution is accompanied by the downregulation of the default-mode network (DMN). In the context of creativity research this finding is particularly intriguing because the DMN is associated with habitual thought and behavior patterns which are hypothesized to be negatively correlated with creativity and the generation of novel ideas. That is, downregulation of the DMN by psychedelics and the accompanying phenomenology of ego-dissolution are promising factors for the understanding (and enhancement) of creativity[281].

Based on these findings, we suggest a novel neuropsychopharmacological mechanism for the enhancement of creativity which has, to our best knowledge, never been proposed before. We would like to emphasize the importance of ego-dissolution for the enhancement of creativity, that is, a reduction of the influence of the ego (DMN) on perception and cognition enables the percipient to perceive reality from a new (more unbiased) perspective. Based on the hypothesis that ego-dissolution provides a "cognitive reset" which enables us to perceive and conceptualize reality from a more

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[280] Furthermore, the authors argue convincingly that the notion that LSD (and other psychedelics) "expand" consciousness is quantitatively supported by their data. Specifically, they argue that the neurophysiological changes associated with psychedelic states contrast with states of diminished consciousness (e.g., deep sleep or general anesthesia). The obtained results are congruent with the idea that psychedelic and unconscious states can be conceptualized as polar-opposites on a continuous spectrum of conscious states. Furthermore, the authors suggest that the level of consciousness is quantitatively determined by the level of neuronal entropy (in accord with the entropic brain hypothesis formulated by Carhart-Harris et al., 2014). It has been suggested that Aldous Huxley "reduction valve" hypothesis appears to be relevant in this context.

[281] Recent evidence focusing on changes in the coupling of electrophysiological brain oscillations by means of transfer entropy suggests that serotonergic psychedelics temporarily change information transfer (via an increase of entropy?) within neural hierarchies by decreasing frontal of top-down control, thereby releasing posterior bottom-up information transfer from inhibition (Francesc Alonso et al., 2015).

unconstrained non-dualistic perspective, we argue that 5-MeO-DMT is an especially intriguing molecule because its effects are much more pronounced than those of psilocybin or LSD. The "reset theory" is a first attempt to conjecture a causal mechanism which could explain why ego dissolution associated with the hypothesized increase in creativity. See things with new eyes (entropy) with reduced influence of perceptual schemata an a reduced top-down influence (i.e., preconception vs. apperception). In sum, we argue that (e.g., psilocybin, DMT, 5-MeO-DMT) are catalysts for though, imagination, understanding, and epiphany.

Ego-dissolution

Empirical data indicates that ego-dissolution is a unique property of certain classes of psychedelic substances (Nour, Evans, Nutt, & Carhart-Harris, 2016b). In a web-based study utilizing the Ego-Dissolution Inventory (EDI) several substances were compared and the results showed that only psychedelics induced a compromised sense of self. In the same study, participants also responded to a subset of items from the Mystical Experiences Questionnaire (MEQ) with a significant factor loading on "mystical experience" a defining feature of which is "unitive" (i.e., non-dual) experience, as has already been pointed out by William James more than a century ago (James, 1985/1902). Again, the results indicated that higher MEQ-scores were associated with psychedelic substances but not with other psychoactive substance like alcohol or cocaine.

5-MeO-DMT: An endogenous catalyst for creativity?

5-MeO-DMT (5-Methoxy-N,N-dimethyltryptamine) is a relatively unknown member of a group of naturally-occurring psychoactive indolealkylamines. It is an analog of tryptophan and endogenous to human physiology (Shen, Jiang, Winter, & Yu, 2010). Its extremely powerful acute effects are pharmacokinetically short-lived. As many other tryptamine psychedelics, it acts as a nonselective 5-HT agonist and causes a broad spectrum of highly interesting psychological, effects. It displays a high binding affinity for the 5-HT_{1A} and 5-HT_2 and subtypes (Krebs-Thomson, Ruiz, Masten, Buell, & Geyer, 2006) but other mechanism of actions appear to be involved in its psychoactivity (e.g., inhibition of enzymatic monoamine oxidase activity; but see Nagai, Nonaka, & Satoh Hisashi Kamimura, 2007). 5-MeO-DMT is widespread in the plant kingdom and has been used by shamans for millennia (Torres et al., 1991).

While its structural relative Psilocybin is has only been found in fungi, 5-MeO-DMT is present in various plants, for instance *Virola theiodora* (Agurell et al., 1969), a tree species belonging to the *Myristicacea*e (nutmeg) family. In additions to its relatively widespread phytochemical distribution, it is present in high concentrations in the venom of *Incilius alvarius* (known as the Sonoran Desert toad), an *Amphibia* which produces significant amounts of 5-Meo-DMT in its numerous parotoid glands as a defensive chemical mechanism against predators (Erspamer, Vitali, Roseghini, & Cei, 1965; Hutchinson & Savitzky, 2004). The salience of toad symbolism in Mesoamerican art and mythology is well documented by anthropologists and toad effigies (with oftentimes accentuated glands) are prominent in the historical remains of the Mayan and Aztec cultures (Davis & Weil, 1992). Moreover, 5-MeO-DMT can sometimes be found in certain variations of Ayahuasca (a drinkable plant-based concoction, which is utilized by indigenous tribes in the Amazonian rainforest for divinatory and healing purposes), for instance, when the leaves of the plant "chaliponga" (*Diplopterys cabrerana*) are added to the concoction (J. C. Callaway et al., 2006; Rätsch, 1998). 5-MeO-DMT has been utilized for spiritual purposes as a religious sacrament in the rituals of the USA based Christian "Church of the Tree of Life" (Gottlieb, 1994). Modern artworks inspired by 5-MeO-DMT experiences are oftentimes geometrically complex and reminiscent of multidimensional fractal-like mathematical structures. Despite its longstanding usage in the course of human evolution[282], systematic research is hitherto very limited and science does not know much about the psychological effects of 5-MeO-DMT. It has been convincingly argued that it is of is of "potential interest for schizophrenia research owing to its hallucinogenic properties" and that research on 5-MeO-DMT can "help to understand the neurobiological basis of hallucinations" (Riga, Soria, Tudela, Artigas, & Celada, 2014)[283] even though visual hallucinations are much less commonly reported compared to its structural analog N,N-Dimethyltryptamine (DMT) which induced the most spectacular vivid visual perception possibly imaginable (Strassman, 2001).

5-MeO-DMT exerts extremely profound effects on the self-concept (ego). Here, the term ego is not used as defined in the classical Freudian tripartide model (Freud, 1923), but it refers to the concept of identity i.e., who we think we are as human beings. Thus, the usage of the term ego is more closely aligned with the ancient Sanskrit term "Ahaṃkāra" as defined in Vedic philosophy (cf. Cartesian positional identity; Comfort, 1979). In this theoretical/phenomenological framework, the ego can be conceptualized as a filter or a lens which converts experiences. Pure awareness, on the other hand, lies beyond the ego construct and is "that which perceives". While the ego identifies with

[282]The long history of human usage of this naturally occurring compound in various cultures suggests that it does not convey a significant disadvantage in terms of evolutionary fitness i.e., natural selection (cf. Martin & Nichols, 2017). Profit-oriented pharmaceutical companies, on the other hand, actively market patented synthetic designer drugs which do not have any evolutionary track record and might cause all kinds of unforeseen neurological, genetic, and epigenetic problems in the long run (cf. Y. Kim et al., 2009), for instance, the widespread prescription of methylphenidate (e.g., Ritalin) in preschool children (Keane, 2008), based on questionable DSM-5 nosology (Phillips et al., 2012b, 2012c, 2012d, 2012a). In contrast to patentded pychopharmcological agents, there is no revenue model for psychedelics in the classical sense.

[283] An animal neuroimaging study conducted by Riga et al. (2014) showed that 5-MeO-DMT decreased BOLD responses in the striate cortex (V1) and the medial prefrontal cortex (mPFC).

the content of sense experience, awareness itself does not (Sivananda, 1972). Awareness itself has no associated identity. It is a detached witness of experience[284].

5-MeO-DMT can occasion extremely profound non-dual experiences and it is much more potent than its structural relatives (e.g., N,N-Dimethyltryptamine), psychologically and quantitatively in terms of dosage. It has been described as a prototypical entheogen (Metzner, 2015).

Given its phenomenological profundity and its unparalleled efficiency to dissolve ego structures we propose that 5-MeO-DMT should be systematically investigated in order to elucidate the postulated connection between non-dual (ego-less) states of consciousness and the stipulated associated enhancement in creativity. The main idea is that ego-dissolution is associated with a breakdown of linguistic structures (hence the ineffability of its phenomenology). According to the Saphir-Whorf hypothesis of linguistic relativism, language structures cognition and perception in significant ways. Ergo, we hypothesize that a release from the strong aprioristic influences of linguistic processes enables a more unrestrained style of cognition and perception. We argue that the collapse of the "subject versus object" dichotomy into a non-dual experience has enormous potential for complex cognitive restructuring. "Ego death" (ego-dissolution) is emotionally and cognitively extremely challenging which resonates with the "hardship model of creativity" (Forgeard, 2013). The experiences induced by 5-MeO-DMT are tremendously radical[285] and therefore capable to disperse

[284] Note that this statement is not an objective empirically validated ontological fact. It is based on qualitative phenomenological experiences often induced by ego-dissolution (e.g., caused by meditation, introspection, psychedelics, spontaneous epiphany, etc.). Ego-less pure awareness plays a central role in many ancient philosophical schools of thought (Mahayana and Zen Buddhism, Advaita Vedanta, Taoism, Sufism, ect. pp.).

[285] It has been argued elsewhere that "increased creativity may … constitute a manifestation of posttraumatic growth, defined as retrospective perceptions of positive psychological changes that take place following experiences of highly challenging life circumstances" (Forgeard, 2013, p. 245).

deeply engrained cognitive/perceptual schemata[286], thereby enabling a more unrestricted style of cognition[287]. Specifically, we argue that it facilitates a less self-centered and hence more unbiased style of cognition. This hypothesis is empirically testable hypothesis which is experimentally falsifiable in the Popperian sense. Various cognitive testing procedures[288] could be utilized to investigate this claim. For instance, we predict a reduction of various cognitive and perceptual biases (Kahneman & Tversky, 1974) after 5-MeO-DMT administration due to enhancements in "openness to experience" (cf. MacLean et al., 2011; Silvia et al., 2009) and alterations in "epistemic style" (Eigenberger et al., 2007). Various dual-process models of cognition (Jonathan St B T Evans, 2008) might prove to be relevant in this context. Limitations of space do not allow us to discuss the multifarious details of this empirical agenda. Hence, we leave the reader with the adumbration that 5-MeO-DMT might be a very fruitful neurochemical research tool for future neuroscientific/psychological studies[289], specifically in the context of ego-dissolution and the catalysis of creativity. Anecdotal evidence suggests that creativity originates from states of mind in which the ego-function is reduced, and mental contents are allowed to "flow" in an uninhibited manner. Both artists and athletes understand that thinking can interfere with creative

[286] Interestingly, preliminary evidence suggests that it is effective in the treatment of addiction, depression, and obsessive-compulsive disorders (Bogenschutz et al., 2015; Carhart-Harris, Bolstridge, et al., 2016). This is congruent with the formulated idea that 5-MeO-DMT has the potential to change persistent habitual modes of thought.

[287] This idea could be empirically tested, for instance, by utilizing a semantic priming paradigm in order to investigate spread of activation (as proxy for verbal creativity). Exemplary studies have been conducted with the dopamine precursor L-Dopa by, for example, Kischka et al. (1996) in order to elucidate the role of dopaminergic neurotransmission in verbal creativity. Anecdotal evidence suggest that serotonergic psychedelics can enhance verbal creativity significantly (longitudinally). In the acute phase, many psychedelics interfere strongly with the linguistic system (a breakdown of semantic and syntactic facilities is oftentimes reported). Interesting, glossolalia is reported in a few cases.

[288] It should be noted that psychedelic might cause serious psychological harm to certain populations with psychopathological dispositions (e.g., specific 5-HT receptor polymorphism). Ergo, careful a priori screening is crucial for ethically responsible research.

[289] 5-MeO-DMT has a very fast onset and a short duration (< 1 hour as opposed to opposed to the long duration of LSD and Psilocybin (several hours) which makes it particularly attractive from a methodological point of view.

performance. This theory is congruent with various dual-system accounts of cognition (Eigenberger et al., 2007; Jonathan St B T Evans, 2008; Kahneman, 2003), i.e., system 1 processes are less constrained by system 2 processes leading to a more "unconstrained style of cognition").

The logical which undergirds our theorizing can be formalized as a syllogistic deductive argument (*modus ponens*):

1st premise:	The phenomenological experiences associated with ego-dissolution enhance creativity.
2nd premise:	5-MeO-DMT catalyses ego-dissolution.
∴ Conclusion:	Ergo, 5-MeO-DMT enhances creativity (via the proxy of ego-dissolution).

Based on this background, we postulate the following more specific directional hypotheses:

Hypothesis 1: The intensity of ego-dissolution experienced by participants predicts the longitudinally measured significance of the life-event in a non-linear dose-dependent manner (Griffiths, Richards, Johnson, McCann, & Jesse, 2008).

Hypothesis 2: Self-reported ego-dissolution predicts subsequent enhancements in creativity, as quantified by various test batteries (e.g., J. C. Kaufman, 2012). This effect is mediated by the profundity of the experience, e.g., how challenging the experience was, intensity of the "peak experience" , personal meaningfulness of the experience, etc. (Barrett, Bradstreet, Leoutsakos, Johnson, & Griffiths, 2016; Forgeard, 2013; Griffiths et al., 2006; Majić, Schmidt, & Gallinat, 2015).

Hypothesis 3: The intensity of 5-MeO-DMT induced ego-dissolution predicts consequent increases in aesthetic perception/apperception, biophilia, and feelings of fundamental existential interconnectedness (viz., "nonduality").

We argue that the hypothesized effects are objectively quantifiable (i.e., measurable) and repeatable in rigorously controlled experimental settings.

Brains in chains: Neurodiversity and cognitive liberty

The UK is the first country in human history which generically bans all psychoactive substances, i.e., an omnibus prohibition of all mind-altering chemicals, irrespective of their well-documented historical use and their safety profile, for example, as objectively quantified by the conventional LD_{50} and TD_{50} toxicity indices. For instance, psilocybin exhibits remarkably low toxicity. The LD_{50} in humans remains unknown, given the lack of any intentional or accidental poisoning death data. The therapeutic window (or pharmaceutical window) is extremely safe and the maximum tolerated dose (MTD) is very high, i.e., the therapeutic index is very high.[290] A common metric in comparative risk assessment is the margin of exposure (MOE), defined as the ratio between the toxicological threshold (defined as the benchmark dose) and the estimated average human intake (Lachenmeier & Rehm, 2015). Both, MTD and MOE indicate a very benign safety profile for psilocybin, especially compared to neurotoxic agents like alcohol which has a very low MOE (Lachenmeier & Rehm, 2015) and has been associated with numerous detrimental neurocognitive (Weitemier & Ryabinin, 2003), genetic, and epigenetic effects (Y. Chen, Ozturk, & Zhou, 2013). Despite these factoids, psilocybin is classified as a class A substance in the UK[291]. This Regulation is

[290] Alcohol, which is legal and indeed systematically promoted by the alcohol industry, has a very unsafe LD_{50} profile and is proven to be neurotoxic (R. Da Lee et al., 2005; Jacobus & Tapert, 2013). Recent longitudinal research has shown that even moderate alcohol consumption has detrimental effects on various neuroanatomical structures (e.g., hippocampal atrophy). Psilocybin, on the other hand, has been shown to induce neurogenesis in the hippocampus in animal studies (Catlow et al., 2013).

[291] In the USA it is also in the highest category (Schedule 1) even though none of the classification criteria apply to psilocybin. For instance, to be classified as a Schedule 1 substance, a given chemical must have "high potential for abuse" and "no accepted medical use". Both criteria do not apply to psilocybin which has been successfully used in medical contexts to treat addiction (Bogenschutz & Johnson, 2016) and depression (Griffiths et al., 2016), *inter alia*. Ergo, the classification is clearly not rationally justifiable, but see https://www.dea.gov/druginfo/ds.shtml

a *lex specialis*, which introduces an additional serious burden for researchers interested in non-ordinary states of consciousness. Regrettably, scientific research on psychedelics is currently legally highly restricted due to the irrational Class A status of psychedelic substances as defined in the "Psychoactive Substances Act[292]" (PSA) which reached Royal Assent in January 2016. The PSA generically prohibits *all* mind-altering substances besides the most harmful and addictive ones which are of commercial significance (e.g., alcohol and tobacco; but see Nutt, King, & Phillips, 2010) and it classifies relatively harmless substances like psilocybin on par the most harmful and detrimental substances like heroin, cocaine, and alcohol. This classification is based on the assumption that psilocybin has no medicinal value which is clearly not the case (but see Bogenschutz & Johnson, 2016). The widespread psychological propaganda (E. L. Bernays, 1928, 1936; Mullen, 2010) against psychedelics (linking psychedelic use to psychopathology and suicide) which was initiated by Nixon's "war on drugs" campaign, has now been evidently debunked (Johansen & Krebs, 2015), even though the public mind is still under its influence. Well informed legal scholars interpret the PSA as an explicit violation of the right to mental self-determination (i.e., cognitive liberty; Walsh, 2016) – particularly in the context of Article 9 of the European Convention on Human Rights which should protect the right to freedom of thought. Freedom of thought is an axiomatic precursor to various other liberties like the freedom of speech. Or as United States Supreme Court formulated it: "freedom of thought … is the matrix, the indispensable condition, of nearly every other form of freedom" ("PALKO v. STATE OF CONNECTICUT," n.d.). Furthermore, it is self-evident that cognitive liberty is a prerequisite for creativity. It can be convincingly argued that the PSA reduces neurodiversity - it homogenizes cognitive/neuronal processes and restricts

[292] For more information see http://www.legislation.gov.uk/ukpga/2016/2/contents/enacted

memetic and, ergo, cultural memetic evolution (in analogy with the importance of genetic diversity in the context of biological evolution). Humanity does not know which ideas will be important in the future. Memetic variability is as important to humanity as is genetic variability due to the unpredictability of future environments.

Summa summarum, the PSA is factually not evidence-based and presents a serious legal impediment to scientific research, neurodiversity, and creativity (see also Boire, 2000).

Conclusion

We would like to close with some general remarks. So far, contemporary science has largely neglected the extraordinary experiences catalyzed by psychedelics. In his classic book entitled "The structure of scientific revolutions", Thomas Kuhn pointed out that it is general phenomenon that paradigm challenging anomalies "that subvert the existing tradition of scientific practice" (T. Kuhn, 1970, p. 6) are neglected as long as possible. Research on psychedelics might force us the rethink our most fundamental beliefs about the way we conceive reality and practice science (e.g., the stipulated dichotomy between observer and observed; physicalism/the brain *produces* consciousness, etc.) and is therefore implicitly perceived as a threat to the widely adopted "quasi-Newtonian" status quo which, in reality, has already been thoroughly revised by quantum physics (e.g., the implications of violations of Bell inequalities for "local realism", Gröblacher et al., 2007; Handsteiner et al., 2017). A detached dualistic "objective" science is no longer possible due to the firmly established holistic nature of quantum entanglement (Horodecki, Horodecki, Horodecki, & Horodecki, 2009). If science wants to live up to its ideal to capture reality in its entirety without leaving any residue, then it needs to integrate psychedelics into its modelling efforts – especially given the fact that many psychoactive alkaloids are endogenous components of human neurochemistry and ergo arguably of evolutionary relevance. Any model which incorporates only a specific (selected) subset of the available quantitative and qualitative data is necessarily at best incomplete (and in the worst case scenario prejudiced, dogmatic, and systematically biased). We are confident that a mature science will sooner or later investigate these naturally occurring compounds in the context of human psychology. It's just a matter of time…

We would like to close with an apposite quote from William James (who experimented with Nitrous Oxide and the psychedelic Mescaline himself). He articulated in his classic "Essays in Radical Empiricism":

"*To be radical, an empiricist must neither admit into his constructions any element that is not directly experienced, nor exclude from them any element that is directly experienced*" (James, 1912/1976, p.42).

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Educational background

2005: Gertrud-Bäumer Berufskolleg Duisburg, Germany. *Abitur*
2005-2009: Free University of Amsterdam, Netherlands. *Scientiæ Baccalaureus* (Bachelor of Science) in Psychology. Supervisor: Dr. Karen Mortier
2009-2010: University of Plymouth, United Kingdom. *Magister Scientiæ* (Master of Science) in Psychological Research Methods (with distinction). Supervisor: Prof. Simon Handley

Research experience

I started studying psychology at the Free University of Amsterdam. My bachelor studies (supervised by Dr. Karen Mortier) were conducted within the theoretical framework of embodied cognition. In our experiments, we utilized different mood induction techniques in order to empirically investigate their influence on selective attention in a series of computerized visual search tasks. Our theorizing was significantly influenced by considerations regarding conceptual metaphor theory and the neuropsychological valence model of lateralised hemispheric processing of emotion perception. Subsequent to my bachelor studies, I successfully completed a M.Sc. in psychological research methods at the University of Plymouth. During my master's project, I collaborated with Prof. Simon Handley and the resulting dissertation focused primarily on the role executive functions play in syllogistic vs. belief-based reasoning (i.e., syntax vs. semantics in belief bias). Much of the motivation for our experimentation was derived from prior work on ego-depletion and contemporary dual process theories of cognition. Based on this background, I acquired substantial knowledge in cognitive psychology, particularly in the domain of reasoning and decision making (e.g., in the Kahneman and Tversky research tradition).

Technical skills

I am a web and UI designer and proficient with modern information technologies (HTML, CSS, JavaScript, PHP, etc.). Shortly after finishing my masters in psychological research methods I started a webdesign company in Germany.

Personal interests

I am intrinsically very interested in the 5-hydroxytryptamine system and its role in perception and cognition (for instance, creativity, neuroplasticity and neurogenesis). Furthermore, philosophy of science and mind capture my deepest curiosity. Personally, I love to exchange ideas with scholars who adhere to different scientific paradigms because interdisciplinary discourse offers great intellectual stimulation and provides impetus for the development of novel unconventional ideas.

"Be less curious about people and more curious about ideas." ~Marie Curie

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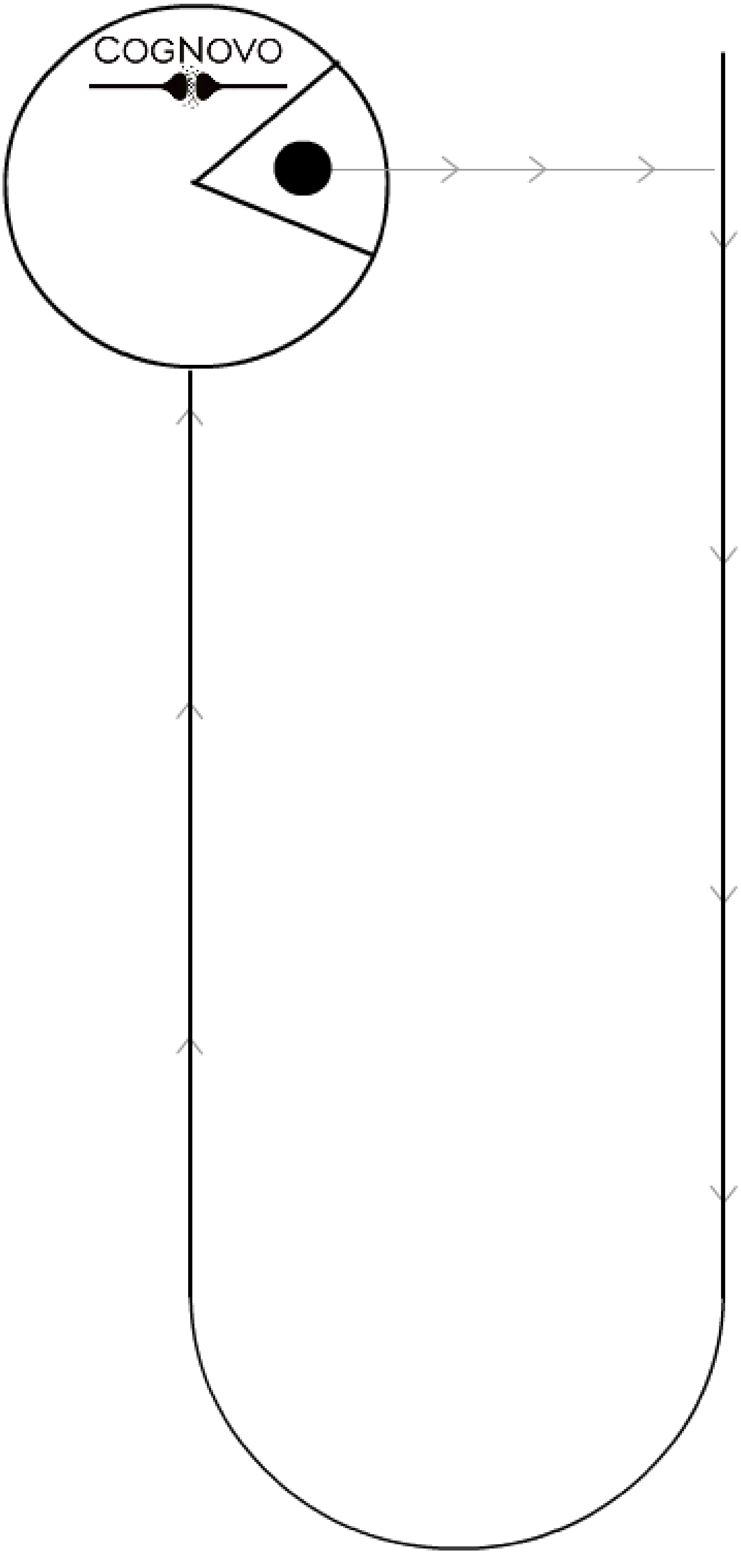
End of thesis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