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THE POTENTIATION OF ACTIONS BY VISUAL OBJECTS

by

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A thesis submitted to the University of Plymouth
in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

Department of Psychology
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Michael Richard Edwin Tucker

The Potentiation Of Actions By Visual Objects

ABSTRACT

This thesis examines the relation between visual objects and the actions they afford. It is proposed that viewing an object results in the potentiation of the actions that can be made towards it. The proposal is consistent with neurophysiological evidence that suggests that no clear divide exists between visual and motor representation in the dorsal visual pathway, a processing stream that neuropsychological evidence strongly implicates in the visual control of actions. The experimental work presented examines motor system involvement in visual representation when no intention to perform a particular action is present. It is argued that the representation of action-relevant visual object properties, such as size and orientation, has a motor component. Thus representing the location of a graspable object involves representations of the motor commands necessary to bring the hand to the object. The proposal was examined in a series of eight experiments that employed a Stimulus-Response Compatibility paradigm in which the relation between responses and stimulus properties was never made explicit. Subjects had to make choice reaction time responses that mimicked a component of an action that a viewed object afforded. The action-relevant stimulus property was always irrelevant to response determination and consisted of components of the reach and grasp movement. The results found are not consistent with explanations based on the abstract coding of stimulus-response properties and strongly implicate the involvement of the action system. They provide evidence that merely viewing an object results in the activation of the motor patterns necessary to interact with them. The actions an object affords are an intrinsic part of its visual representation, not merely on account of the association between objects and familiar actions but because the motor system is directly involved in the representation of visuo-spatial object properties.

AUTHOR'S DECLARATION

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

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To my parents and to Suzy

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1. Chapter 1 : Introduction

The work described in this thesis is based on an idea about the relation between visual representation and action. Few people would hesitate to assert that the primary function of vision is to control actions, and yet the two disciplines have been studied far too often in isolation. This has been especially true of the computational or 'information processing' approach to perception and action. Marr's (1982) seminal work on vision did much to bring to the forefront the computational problems involved in deriving useful descriptions of the visual world. Much of the work that the computational approach has spurred has to do with object *recognition*. How can an unambiguous description of an object be derived from the very variable light patterns available at the retina? Object recognition is a huge computational problem but it is only half of what vision is about. There is a sense, too, in which problems of object recognition lend themselves to isolated study. The success criteria for deriving a representation that adequately identifies instances of a particular object do not depend on the body in which the identifier is housed. In contrast, using vision to guide actions depends critically on the motor systems in which the visual device is embedded. A central theme of this work is that it is not only the way vision is *used* that depends on the physical systems of the perceiver, but also the manner in which visual representations are *formed*.

The distinction between the use of vision for recognition and for action is reflected in the division of the visual system of humans and primates into two major processing pathways: the dorsal and ventral streams. The nature of the two pathways and the processing characteristics of the dorsal system and its relation to the motor systems is discussed in Chapter 2. Knowledge of the way visual information is used for the guidance of actions is rapidly increasing but the approaches taken, whether from neurophysiological studies or behavioural ones, almost always have, as a starting point, one central assumption. This is that any understanding about the way visual information is used to control motor output can only be observed under explicit goal directed actions, where animals or humans make intentional movements toward a visual object. This paradigm itself results from the almost universally held view that motor system involvement necessarily waits until a visual object has become a goal for a specific action. Once this has happened translation processes begin that result in visual information about the goal object being transmitted to the motor systems, which in turn convert this into appropriate muscle commands. This view has intuitive appeal - it is easy to conceptualise visually guided action as involving two broad classes of representation, visual and motor, and one process, the translation of visual information into motor commands. However, this conceptual distinction is not well reflected in the organisation of the visuomotor system. It is not possible to say where visual processing ends and motor processing begins and large groups of cortical cells have response properties that are only appropriately described by the term 'visuomotor' rather than visual or motor. Though the high degree of visuo-motor integration is well known it is nevertheless assumed to reflect only the nature of *translation processes* that occur during goal directed acts. There is no sense in which motor or even visuomotor involvement is thought to occur during the perception of an object when no explicit intention to act toward it is present. The major aim of the work presented here is to establish the existence of motor involvement in the visual representation of objects in the absence of explicit intentions to act towards those objects. This idea sits quite easily with what is known about the visuomotor systems, although this evidence by itself does not point one way or the other. Single cell recording experiments, for instance, may go some way towards expanding our understanding of the complexity and diversity of the information processing in the visual and motor systems but they do not provide much insight into the functional characteristics of this processing.

It is not the aim of the experimental work undertaken here to specify, in any fine detail, the nature of the motor system's involvement in visual representation. What is argued for can be stated quite simply: that the actions an object affords are represented when it is viewed. These actions are an intrinsic part of the object's visually derived representation and they do not depend on some decision to act already being present. As it stands such a proposal says nothing particularly radical. Over a life history we build up strong associations between commonly performed actions and visual objects, so it would not be surprising, for example, if the sight of a football brought with it thoughts of kicking. The proposal is, however, more than something about built up associations between actions and objects. It concerns actions not merely as associations but as directly involved in the visual representation of an object.

The idea can be put another way. The visual system has to represent object properties in a manner that enables successful interactions with objects. The primary purpose that visual representations of objects serve *in an action context* is to provide spatial information about their properties in relation to the body parts that must interact with them (or avoid them). This is not to say that other information is not important in determining what actions can or, should, be carried out given the presence of a visual object. We are not (usually) stimulus driven, after all. Visuo-spatial information about the position and size of an object is not sufficient to determine appropriate actions. Whether we reach out for, or try to avoid, an approaching object obviously depends both on the context of the action and on knowledge about the object which is not simply visuospatial. Higher level knowledge about object properties and their function must be able to influence the actions we direct toward them. Nevertheless these higher level actions are dependent on certain low-level action relevant information being available. Making this information available directly, without the need for computations to be performed on an internal model of objects in space and their relation to the body, is made possible by actually using the motor system to represent them. There is little to be gained, for example, by building a universal representation of the environment and the objects it contains, if performing any action requires a complex conversion from this representation to one suitable for programming the action. This point has been well made by Stein (1992) with regard to our representation of egocentric space (see Chapter 2). The action potentiation account examined in the experimental chapters proposes that visual properties such as object orientation, size and position are represented within the visuomotor system. Representing the location of an object is achieved by the partial activation of the motor commands that are required to bring the hand into contact with the object. Likewise representing the orientation of the object can be achieved by directly activating the motor patterns involved in bringing the wrist into the correct orientation for a successful grasp. Such a representational scheme makes action relevant information about the object available directly. In the absence of explicit intentions to make a particular action the representation of an object property is likely to be carried out in multiple effector systems, each representing that property in a manner that makes the relation between the object and the actions the effectors can be used for, explicit. Which are actions are most highly activated will depend upon both intrinsic object properties such as its shape and size, as well as extrinsic ones such as its location. Reaching and grasping is an action most likely to be activated by objects located within arms reach and possessing a major axis that is small relative to the hand. The experimental work described in later chapters focuses on components of the reach and grasp movement and their activation by visual objects within the reaching space.

2. Chapter 2: Visually guided reaching.

2.1. Introduction

This chapter reviews the aspects of the human and primate visuo-motor system of relevance to the hypothesis of action potentiation. The material comes from several sources. First there are problems involved in performing any visually guided movement that are purely computational in nature. Computational models of visually guided reaching highlight the difficulties involved in transforming visual information about the spatial location and form of an object, into a set of motor commands that result in a successful interaction with an object. From a computational point of view the task is ill posed - the human effector system has excessive degrees of freedom with which to accomplish any given movement; a feature which has come to be known as Bernstein's problem (Bernstein, 1967). No attempt is made to cover, exhaustively, the enormous number of computational models of visually guided action. Instead a selection of models that derive their success from their adoption of constraints based on the biology of the visuo-motor system are discussed. These models are important to the hypothesis under examination in as much as they all hinge upon the notion of learning a mapping between a visual input and a successful action without resource to the explicit computation of such a trajectory. A second source of information comes from behavioural studies of reaching in human subjects. There is quite consistent evidence from such studies that human prehension is divided into two major components: reaching to the target and preparing the hand shape for it. Despite the fact that the preshaping or manipulative component unfolds at a later stage than the transport component both appear to be represented before movement onset, a property which is important for the action potentiation account as it allows for the possibility that these components are represented simply by viewing the object. A third source of important information comes from the neurophysiology of the visuo-motor system. This is discussed in some depth as much of what is currently known about the organisation of this system is entirely consistent with the action potentiation hypothesis outlined in the introduction. This section centres around the notion of two visual systems and the highly distributed and integrated nature of visual and motor representation. Of special relevance is the notion that no clear divide exists between purely visual and purely motor representation, a point that is of great importance in the notion of action potentiation.

Reaching and grasping a visual object requires converting information about object properties, originating in the occipito-parietal system, to a set of muscle commands that transport the hand to the object, and preshape it, to enable a stable grasp to be achieved. From an engineering perspective this task can be viewed as a series of steps that transform information about the spatial properties of the object into a set of motor commands that result in a successful movement. In biological systems, however, these processes are neither carried out in series nor in a manner that involves the explicit computation of the underlying formal steps. Even in a multi-joint system whose physical characteristics remain stable, no unique solution exists to the inverse kinematics problem of choosing a series of joint angles from the initial through to the final posture. For example, given a prespecified path of the hand, there is an infinite number of combinations of shoulder, elbow and wrist angles that can produce *each point* of the trajectory, and obviously an even greater number if one adds further degrees of freedom by allowing movement of the trunk. This problem is further compounded in biological systems because the physical properties of the musculature and joints do not remain stable but change over time, both in the short term after fatigue or damage, and in the long term during an organism's growth and aging. Despite this, most natural reaching movements to objects exhibit stereotypical patterns with characteristic bell shaped velocity profiles and roughly straight line hand paths (Bullock & Grossberg, 1989b, Soechting & Terzuolo, 1990; Kalaska & Crammond

1992). This suggests that the motor system utilises certain constraints to minimise the effective choice of trajectories.

2.2. Computational problems

2.2.1. Excess degrees of freedom

From a computational point of view the central problem associated with the planning and execution of reaching movements is the excess degrees of freedom that biological systems possess. This is, of course, an essential property in as much as it allows for flexibility in execution. The hand-arm-shoulder effector system has seven degrees of freedom whereas specifying the position of an object in 3D space only requires six. The redundancy in the system means that for any desired trajectory there is no unique solution to the inverse kinematic transform (translating this trajectory into a set of joint angles) (Hildreth and Hollerbach, 1987). The high level of conformity in human movements is an indication that certain natural constraints are used by the system to effectively reduce the degrees of freedom. Given a particular starting configuration of the hand-arm effector system, for example, not all paths to a desired final position are equally comfortable to execute. The particular constraints that the human effector systems employ is a matter of debate (examples include maximising smoothness of the movement, minimising jerk and employing synergies between joints). Another difficulty is the way spatial information about the target object is initially specified and transformed into the reference frames of the effectors. The location of an object is probably specified in a head centred frame (Zipser & Andersen, 1988) whereas psychophysical measurements indicate that arm movements are coded in a shoulder centred frame (Flanders, Tillery & Soechting, 1992).

2.2.2. Trajectory learning

Most models that aim to explain reaching in humans share certain broad similarities when examined from a relatively high level. They can all be said to involve the learning of a mapping between the target position and the state of the effector system associated with that position, rather than the explicit computation of a trajectory. Where they differ is with respect to how the target position is represented in motor terms and in the execution details of the movement from the present position of the effector to the final, target position. In a model that derives support from the discovery of population coding[1] in the parietal and motor areas Bullock & Grossberg (1989b) (see also Bullock & Grossberg, 1989a; Gaudiano & Grossberg, 1992) describe a process (vector integration to endpoint, VITE) in which the difference between target position and the present position of the hand is rapidly integrated to zero. Their model accounts for a considerable amount of the behavioural properties of reaching movements, including approximately straight line hand paths and bell shaped velocity profiles. For present purposes the most important aspect of the model is that it involves the learning (and continual updating) of a mapping between the position of a target in head centred space and the position of the hand in terms of motor commands (outflow signals). The initial learning phase is postulated to occur during infancy by a process of 'motor babbling' in which the work space is randomly sampled and direct mappings between hand positions and target positions established. Trajectories are not explicitly formulated but arise from the integration process - the present position of the hand is continually updated by an amount and direction corresponding to the difference

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[1] Population codes, which are discussed in a later section, refer to a type of coarse coding employed by groups of cortical cells. In brief, a target position can be specified accurately by a group of cells each being only 'coarsely tuned' to direction. The net sum of the activations of the cells in the group signals a property such as location very accurately.

between it and the target position. Because hand position is specified in terms of motor outflow signals, updating this information automatically results in the hand moving to the new position until the difference between target and hand position is zero. Such a process also allows for rapid on-line trajectory corrections in cases where the position of the target shifts abruptly (e.g. Goodale, Pellison, & Prablanc, 1986). Furthermore trajectories are smooth as the arm moves by changing the muscle length of all the muscles involved simultaneously, by an amount proportional to the difference between their present and final lengths, a process that ensures roughly straight line hand paths.

Rosenbaum and colleagues (Rosenbaum, Loukopoulos, Meulenbroek, Vaughan & Engelbrecht 1995; Rosenbaum, Engelbrecht, Bushe, & Loukopoulos, 1993) have employed a similar approach in which the relationship between whole postures and target positions in space is learned. The model is based on a joint angle representation of postures and assumes that forward kinematics can be computed (finding external spatial positions from known joint angles). Whenever a target object is specified a weighted sum of the contributions of a stored set of postures is derived that is based on their contribution to the final posture, the weights themselves being derived from travel and accuracy costs. Target postures are the weighted sum of the stored postures. A specific movement is executed by having each degree of freedom in the system (each joint angle in their model, as reaches were restricted to the saggital plane) change continuously, and over a similar time course, to the value in the target posture. As in Bullock & Grossberg's (1988) model, but by different means, this results in roughly straight line hand paths.

Sporns & Edelman (1993) argue that movement patterns are selected from a basic repertoire that emerges during development. This initial repertoire has its roots in the evolutionary history of the species. Subsequent movement patterns are selected, somatically, during the lifetime of the organism. This process involves the selection of *whole movement patterns* based on a success criterion (value system) itself pre-specified through evolution. One of the most important properties of this scheme is that the excess degrees of freedom present in the motor system is a necessary prerequisite for adaptive movements to be selected. Because whole movement patterns are the units of selection, synergies emerge naturally, and the excess degrees of freedom in the system allows for a flexible repertoire without causing a computational problem. In organising a basic repertoire of whole movement patterns evolution has effectively reduced the degrees of freedom problem. Like Bullock & Grossberg (1988), Sporns & Edelman (1993) emphasise that more complex movements are learned from spontaneous or exploratory activity. Synergies emerge by virtue of the amplification of successful movements and possible weakening of unsuccessful ones. Thus adaptive movement patterns are discovered rather than explicitly computed. The process is only probaballistic but the success criteria ensure that over time the most adaptive movement strategies will prevail. Thus given that a movement pattern that results in successful contact with an object has adaptive value, it will be reinforced by the diffuse amplification of the neuronal connections subserving it. However, those movement patterns that achieve the same end but with less cost, (which could be measured, for example, in terms of the energy expended), will be reinforced more than less efficient patterns. As a result there will exist competition between whole movement patterns for achieving the same end with the most efficient pattern being reinforced at the other's expense.

Most would agree that the idea that the brain computes explicit trajectories is untenable. What is less obvious is the importance of the interrelation between perceptual and motor processes during the learning and constant updating of visually guided action. This is, perhaps, most explicitly recognised in Sporns & Edelman's (1993) approach. What is learned in order to successfully reach and grasp an object is an entire visuo-motor pattern. We learn to reach for objects not to the locations they occupy. The perception of objects and the planning of motor acts to engage them are not fundamentally separate processes. Both processes rely on each other - actions are required to derive useful visual information from the world as much as vision is required to guide actions. This has important implications for the way visual objects are represented. In particular, and as the neurophysiology of the visuo-motor system suggests, the spatial properties of objects are coded with reference to the effector systems of the organism. Before examining the neurophysiology and associated neuropsychology of the visuo-motor system some of the behavioural data on reaching and grasping in normal human subjects is presented.

2.3. Behavioural studies of prehension

2.3.1. Separate visuo-motor channels

One of the first detailed studies of prehension in humans was carried out by Jeannerod (1981) from which he proposed that prehension movements can be divided into two major components - transport and manipulation. Jeannerod (1981) provided evidence that these two components were dependent on two separate 'visuo-motor channels' each sensitive to specific object properties. The transport component, concerned with bringing the hand to the vicinity of the object was found to be independently affected by object properties such as distance and location whereas the manipulation component, concerned with preshaping the hand for successful interaction, by object size and orientation. Developmentally the two systems emerge at different times, with the transport component being present from birth whilst the manipulation component only emerging after about five months (Hofsten & Ronnqvist, 1988). More recently Gentilucci, Castiello, Corradini, Scarpa, Umiltà & Rizzolatti (1991) modified the 'two channels' hypothesis to allow for the influence of object size on the transport component. They found that the transport profile of reaches to objects was moderated by the size of the object, but this was not attributable to the difference in the grasp types needed to manipulate objects of different sizes. The functional separation of the two stages was still supported from their study as the type of grip used to grasp the object was not responsible for the change in the transport component. The effect of changes in object size amounted to a lengthening of the final deceleration stage of the reaching movement when target objects were relatively small and reflects the increased accuracy necessary to guide the hand to small targets. By comparing pointing movements to targets of different sizes (in which the manipulation component is always the same) with actual reaches (in which the manipulation component is affected by target size) they found that the affect of changes in object size during actual reaches were fully accounted for by the same changes in the pointing task when the manipulation components remained identical. Changes in object location at the start of the reaching movement affect the pattern of grip formation as well as arm transport. Similarly changes in object size affect arm transport as well as grip formation (Jeannerod & Marteniuk, 1992). The temporal relation between changes in the two components is not strict enough to infer a synergy, however and Jeannerod & Marteniuk conclude that the relationship is akin to a co-ordinated structure in which the two separate systems link up for a common task. There thus appears to be reasonable evidence that prehension movements are built up out of functionally separate modules, each sensitive to particular object properties that feed this information into the relevant muscle systems of the hand and arm.

Such an approach to visuo-motor behaviour has been elaborated by Iberall & Arbib (1989). They propose that reaching and grasping movements are composed of a series of perceptual and motor 'schemas' that together combine to form a co-ordinated control program (CCP). The high level CCP essentially corresponds to the goals and intentions of the organism whilst the low level perceptual and motor schemas compete for the control of action. Similar to Jeannerod's (1981) separate channels account each perceptual schema extracts specific information about object properties that are relevant to specific components of the prehension movement. The perceptual schemas input directly to the motor schemas that govern the individual components of the prehension movement and do so in a feed forward manner. The perceptual-motor schemas can therefore be regarded as relatively independent functional units out of which the complete movement is assembled. Perceptual schemas that extract information about object orientation, for example, would feed into motor schemas governing hand/wrist rotation and those extracting information about the size of the opposition space embedded in the object feed this information into motor schemas governing the selection of grasp type (Iberall, Bingham & Arbib, 1986). The basic schemas out of which whole movements are built are stimulus driven and, so long as the overall aim of the organism does not change, will therefore take account of transient changes in target properties automatically by on line adjustments as new perceptual information is fed forward to the relevant motor schemas. The feed forward nature of visuo-motor control is an important property that allows for rapid updating of movements to changing targets without resource to visual feedback of the hand. None of the characteristic motor patterns of arm transport and hand preshaping depend on vision of the hand during a reaching movement (Jeannerod, 1981, 1994). Jeannerod (1994) suggests that the perceptual properties that together constitute an object's affordances (in a representational rather than ecological sense) do not need to be 'bound' together into a single representation, in contrast to the requirements of a representation suitable for recognition. Instead each component of prehension is directly driven by the relevant object properties - each motor component only needing information about a specific subset of the perceptual information available. The notion of separate components of prehension each being driven by distinct perceptual properties is a central theme of the experimental work described in later chapters. From a theoretical perspective the difference in the requirements of a representation for guiding actions and for recognition is of central importance and is reflected in the neurophysiology of the visual system examined in the next section. In particular there is considerable evidence that the human and primate visual system is divided into two major processing streams that use visual information for quite separate purposes. This has come to be known as the 'two visual systems' hypothesis and, although now widely excepted from an anatomical point of view, still remains controversial with regard to the interpretation of the information processing tasks being carried out by the two systems.

2.4. Two visual systems

2.4.1. 'What' and 'Where' pathways.

The notion of two parallel visual subsystems has gained general acceptance since the lesion studies of Ungerleider & Mishkin (1982). They proposed that the dorsal pathway, from the striate cortex to the posterior parietal lobe, was responsible for object localisation, whereas the ventral pathway, from striate cortex to the inferior temporal lobe, was responsible for the recognition of objects. The distinction came to be known as that between the 'what' and 'where' systems (according to Ettlinger (1990) this distinction has often been accepted too readily, without due consideration to what precisely object vision without spatial vision is, and vice versa). Lesions to the posterior parietal cortex result in selective impairment of spatial processing apparent in conditions such as visual neglect and optic ataxia. In contrast, lesions to the inferotemporal lobe specifically affect object recognition and pattern discrimination resulting in visual agnosias. The distinction has some basis in the differential projection to the two systems of the magno and parvo layers of the lateral geniculate nucleus. The separation is not symmetric, however, with the parietal system being dominated by projections from the magno pathway whilst the temporal system receives roughly equal inputs from both pathways (Merigan & Maunsell, 1993). Some of the different properties of the temporal and parietal systems can be explained by reference to the contributions of the magno and parvo pathways. In particular, the temporal pathway's specialisation for colour processing is largely the result of the involvement of the parvo input whilst the parietal system's greater sensitivity to fast moving stimuli results from the greater proportion of magno input (Previc, 1990). However, as a general rule the notion of two parallel visual systems that have their basis in an anatomical separation of parvo and magno cells in the retina is important but over simplified. Both parietal and temporal systems have extensive connections and share many processing properties (Merigan & Maunsell 1993, Goodale, 1993).

2.4.2. Perception versus action.

Despite shared capacities, the output functions of the two systems are quite distinct. The original distinction between spatial and object vision made by Ungerleider & Mishkin (1982) has recently been reinterpreted. On the basis of a striking neuropsychological case, Goodale, Milner, Jakobson, & Carey (1991), Goodale & Milner 1992, Milner & Goodale (1993)recast the distinction as that between perception and (visually guided) action. Their patient, D.F., suffered carbon monoxide induced brain damage of the ventral system (largely restricted to areas 18 and 19). This resulted in a severe visual-form agnosia in which her ability to recognise the orientation and size of objects was extremely poor across a wide variety of response options including verbal report, discriminating between objects and positioning her hand and fingers to indicate the size or orientation of the presented objects. In marked contrast to this perceptual deficit, when required to reach and grasp the same objects, or to 'post' her hand through an oriented slot, her actions were finely tuned to their size and orientation. This dissociation is exactly opposite to that observed in optic ataxia, resulting from damage to the dorsal stream. Patients with this condition experience no deficits in recognising the orientation and size of objects but have severe impairments in directing reaching movements to them (Perenin & Vighetto 1988). The disorder is specific to visually guided reaching - reaching to auditory or somatic targets is normal as are motor, visual field, proprioceptive and visual space perceptual functions. The specificity of the disorder to visually guided reaching is highlighted by the fact that it can be specific to reaches made by a particular hand in a particular hemi-field. Misreaching is mainly confined to 'open loop' conditions in which subjects have no visual feedback of their hands during the reach. Reaching with vision of the hand is slower, but as accurate as normals, and marked improvements are made when vision of the starting position of the hand is available (Jeannerod, 1986). Jeannerod suggests this improvement may result from the ability to re calibrate the position of the hand in body centred co-ordinates and make up for a postulated lack of accurate proprioceptive information during the reaching movement. Importantly, the deficit is not restricted to mis-directing the hand but also involves the inability to correctly adjust the orientation of the hand and position of the fingers to the object's shape (Jakobson, Archibald, Carey & Goodale, 1991; Jeannerod, Decety & Michel, 1994; Jakobson & Goodale, 1994), an observation which supports the view of the dorsal system as involved in all aspects of visuo-motor activity rather than purely spatial localisation. In fact Perenin & Vighetto's (1988) data suggest that preshaping the hand may be more strongly affected, in as much as the failure to preshape the hand occurred even with full visual feedback (closed loop) - a condition in which object localisation approached that of normals.

Taken together, the visual form agnosia present in D.F and the impairments observed in optic ataxics constitute a full double dissociation between visually guided action and the perceptual awareness of object properties. Further investigation of D.F. revealed that her ability to correctly reach and grasp objects relies on quite primitive visual information. For example, when asked to post a T-shaped form through a similar shaped aperture presented at different orientations, she showed correct orientation adjustments on only half the trials (Goodale, Jakobson, Milner, Perrett, Benson & Hietanen, 1994). Significantly, the errors observed in the remaining trials were almost always at right angles to the correct orientation. Thus it appeared that D.F. could only process a single orientation in the stimulus and target during visually guided reaches. More detailed investigation also showed that D.F.'s ability to successfully orient her hand to a single edge depended on information derived from luminance contrast. She was unable to perform the same action when the edge was defined by gestalt grouping principals or complex pattern information, suggesting that in normal subjects the ability to perform accurate reaching and grasping movements to complex objects may rely on connections between the dorsal and ventral stream (Goodale et al., 1994).

The notion of an independent route from vision to action receives further neurological support from three cases reported by Riddoch and colleagues. They report a dissociation between a patient J.B. (Riddoch & Humphreys, 1987) and C.D. (Riddoch, Humphreys & Price, 1989) in the ability to gesture to visually presented objects. J.B., who suffered extensive left hemisphere damage, was relatively good at gesturing the use of visually presented objects that he was unable to name or match according to functional category. He could match the objects when given their names implying that his difficulty was restricted to visually presented objects. In contrast, C.D., who had a unilateral lesion of the left parietal lobe was impaired at making gestures only to visually presented objects. This was restricted to the contralesional hand and to the visual modality. Another patient G.F. reported by Pilgrim & Humphreys (1991) had multiple lesions to the right temporal and frontal lesions. G.F. showed similar symptoms to C.D. but his ability to gesture with his contralesional hand was impaired across all modalities, although worst with stimuli presented by vision alone. The pattern of deficits are explained by the authors as resulting from selective impairments to several available routes from vision to action. Pilgrim & Humphreys (1991) suggest that actions can be generated by three routes. First there is a direct link between visual input and actions in the sense of affordances (e.g., Gibson, 1979). Second there is a route mediated by a structural description of the object. Third, they propose a route from conceptual knowledge as in gesturing the use of an object from its name. Precisely what is meant by the 'affordance route' is not clear- at least in so far as gesturing to objects is concerned. Gesturing *use* requires knowledge of object function, and it remains mysterious how object function could be available directly in the same manner as more traditional ecological invariants, for example, the time to contact of an approaching ball. Object function cannot be derived unambiguously from object shape - the relationship has to be learnt. In contrast a property such as time to contact can be derived without any information about what is about to be contacted. The directness of the affordance pathway, in their sense, cannot be treated in the same way as the use of affordances in the ecological sense. In the latter, an object directly affords an action in virtue of its physical properties taken in conjunction with the physical properties of the perceiver. Actions are afforded because of a particular physical relationship between the world and the organism. In contrast the notion of the direct route proposed by Riddoch and colleagues would have to involve the learning of an association between the visual description of an object and a commonly performed action. It *becomes* direct, presumably, as connections are built up between action patterns and visual patterns which bypass conceptual information and enable the action to be activated without any semantic influence. More recent evidence from normal subjects does appear to confirm the idea that separate routes exist between relatively high level actions and semantic or visual input. Rumiati & Humphreys (1996) found that under forced speed conditions, subjects made quite distinct errors in gesturing to pictures of objects or to object names. For example, when required to gesture to pictures of objects more ‘visual’ errors were made - that is, subjects were more likely to make a ‘writing’ gesture to the picture of a screwdriver than to the name ‘screwdriver’. In the latter condition subjects were found to be more likely to make a ‘semantic’ error, perhaps performing a hammering or sawing action. Such forced errors imply that there are at least two distinct pathways to actions, one based on visual-action associations and the other on semantic-action associations. Neither pathway can truly be said to involve an 'affordance' route, however, as even in the case of the so called 'visual' errors the actions produced related to a learned association between visual shape and object function.

The findings of Riddoch et al. (1989, Riddoch & Humphreys, 1987 and Pilgrim & Humphreys, 1991) in fact fit quite readily into the scheme put forward by Kosslyn (1994) who proposes that both co-ordinate and categorical spatial relations are computed in the dorsal (parietal system). The precise co-ordinate representations of object properties are used to control actions whilst the categorical relations can be used to form a structural description that is then used by the ventral (infero-temporal) system to mediate object recognition and identification and subsequent activation of semantic properties. The major difference between Kosslyn's interpretation of the two pathways and Goodale et al's lies in the proposal that the dorsal / parietal system also computes *categorical* spatial relations, as well as precise co-ordinate relations, with specialisation for the two types of spatial relations encoding occurring in each hemisphere. Automatic activation of quite high level behaviours by visually presented objects can be observed in patients with so called 'utilisation behaviour' (Lhermite, 1983). Presenting objects to such patients often results in the involuntary prehension and subsequent use of the objects. Lhermite argues that the condition, which results from lesions to the frontal lobes, is due to the loss of parietal inhibition. Thus visual attributes of the object generate motor commands that fail to be selectively activated or inhibited by the frontal system. This might explain the condition quite well were it not for the fact that the objects are not only reached out for and grasped (a process the parietal system could easily achieve) but they are also used correctly. The presentation of a knife, fork and plate may automatically elicit the behaviours associated with eating food from the plate. A full explanation of the condition would have, therefore, to assume that there is also a lack of inhibitory control over the actions associated with the objects and not merely over the visuo-motor representations generated in the dorsal parietal system.

2.4.3. Perturbation studies

The dissociation between the perceptual awareness of stimulus properties and visually guided action can be observed in normal subjects during reaching tasks to perturbed targets. In this paradigm subjects reach out to an illuminated target whose position (or size) may change unpredictably at some point during or before the reaching movement. When the position of the target is made to change during the reaction time to the first stimulus and before the reach has been initiated the reaching movement is delayed by an amount approximating one reaction time, suggesting that planning a new trajectory must wait until a new target position is computed (Jeannerod & Marteniuk, 1992). In contrast to the relatively long delays present in the latter conditions, when the target change is time locked to the saccade present at the start of the reaching movement, the movement is corrected on-line, with no increase in overall movement time and no secondary accelerations in the kinematic profile that would indicate that the first movement plan had been aborted and a new one implemented. Goodale, Pelisson & Prablanc (1986) monitored the effect of small changes in target distance. On half the trials subjects were initially presented with a centrally placed target that jumped to a position 30, 40 or 50 cm to the right and stayed there until the pointing movement was finished (single step condition). They were instructed to point to the new target location as quickly as possible. On the remainder of the trials the initial movement of the target was followed by a small secondary movement whereby the target moved back to a point ten percent more distant (double step condition). This secondary movement occurred at the time of maximum velocity of the saccade accompanying the initiation of the reaching movement and was, therefore, not noticeable to the subjects. In both conditions subjects' hands and arms remained invisible. In both double and single step trials subjects consistently undershot the target. Most importantly the amount by which targets were undershot in each condition was the same and movement times and trajectory profiles in the double step condition were identical to those that would have been made in single step trials. Thus, without vision of the hand or perceptual awareness of any change in target position subjects' trajectories were corrected on-line. An elaboration of this approach to examine changes in target direction that involved alterations in the direction of curvature of the hand trajectory was carried out by Prablanc & Martin (1992). This experiment was similar to that of Goodale et al. (1986) except that target directions were displaced under both open and closed-loop conditions. The results showed the same pattern. On double step trials subjects' trajectories were corrected on-line, although movement time increased slightly (between 66 and 80 msec.). The authors suggest that this increase probably reflects the increased complexity of altering direction as opposed to amplitude. The increased time of 66-80 msec. is, however, shorter than the minimum time required for visual or proprioceptive feedback of hand position, which would be available in the closed-loop condition. This, and the fact that trajectories were similar in both conditions, implies that the mechanisms involved in correcting trajectories to a target do not depend on vision of the hand, as proposed by Goodale et al. (1986). Instead, on-line corrections of hand trajectory appear to be based on a combination of target position and efference copy information about hand position (Jeannerod & Marteniuk, 1992; Bullock & Grossberg, 1988).

The experiments of Prablanc & Martin (1992) and Goodale et al. (1986) involved pointing movements rather than reaching movements terminating in a grasp. Paulignan, MacKenzie, Marteniuk & Jeannerod (1991) conducted a similar experiment in which subjects had to reach and grasp illuminated dowels that could change position at the beginning of the movement. Although in this case the change in dowel position on perturbed trials was not time-locked to occur with the saccade present at movement initiation, the data shares many properties of the studies involving perturbations of location and distance. First of all the movement times increased by no more than 100 msec., implying that the movement was rearranged on-line, despite the fact that changes in the dowel position required complex adjustments in the wrist and finger configuration. Second, although subjects were aware of the changes in target position their estimates of when the changes occurred were highly inaccurate. In most cases subjects reported experiencing the change as their hands neared the object and even, in some cases, after object contact. In a similar way to the unconscious correction of reaches to undetected target changes, these subjects performed motor corrections long before any experience of the change. Jeannerod, Paulignan, MacKenzie & Marteniuk (1992) examined perturbations of object size. Here an illuminated dowel could change from small to large or vice versa at the moment the reach was initiated. In contrast to the effects of perturbations of location during goal directed reaches the earliest observable changes in prehension occurred after 300 ms. Jeannerod et al. (1992) interpret this result as a consequence of the two visuo-motor channels hypothesis of Jeannerod (1981). They suggest that representing object size, (and therefore also changes in object size), involves processing in the systems responsible for object recognition and identification (i.e. the ventral system), processing which takes longer than that in the dorsal stream (see also Castiello & Jeannerod, 1991). However this result may simply reflect the fact that changes in object size are much more noticeable than changes in location resulting in a conscious reprogramming of the motor command at the expense of on-line corrections. The data from D.F. indicate that object size is capable of being processed by the dorsal stream in the absence of any ventral input (or at least that ventral input required for conscious access to object size). It may be the case that, as Jeannerod et al. (1992) suggest, correcting distal components of prehension is a slower mechanism than correcting location. However a proper test of this hypothesis would require changing object size during saccades to the object thereby rendering the change imperceptible. Such a study would unfortunately be restricted to very small changes in size if the perturbation was to remain unnoticed after the saccade.

Other studies have observed the dissociation between cognitive and motor function by selectively feeding a signal to one or other system. Bridgeman, Kirch & Sperling (1981) used induced target motion, produced by moving a surrounding frame, to give the perceptual impression that the target had jumped to the right or left. Actual pointing movements to the target location after both it, and the frame, had been extinguished were identical in both left and right induced conditions, indicating that the motor system remained unaffected by the induced motion. In contrast if subjects adjusted the actual motion of the target within the inducing frame until it *appeared* stationary but was now in fact moving, their pointing movements were sensitive to the actual movement and position of the target, even though they perceived it as stationary.

2.5. Unilateral neglect of space

Unilateral neglect most commonly occurs following right side lesions of the parietal lobe, and from other areas of the brain strongly connected to this area (Andersen, 1987). The diversity of symptoms that characterise the disorder reflect the range of visuo-motor transformations that the parietal lobe governs. Although right side neglect can occur following left parietal lobe damage this is much less common than left neglect on account of the right side's specialisation for spatial processing. Patients with left neglect typically fail to be aware of objects to the left of their body midline despite having free eye movements and essentially intact visual fields. Where visual field deficits do exist they cannot account for the observed effects (Bisiach, Beri & Vallar, 1985). A unitary explanation of neglect in terms of the disruption of a single visuo-spatial function is not forthcoming and theories tend to revolve around attentional accounts (e.g., Ladavas, Umiltà, Ziani, Brogi & Minari, 1993; Rizzolatti, Gentilucci & Matelli, 1985) or representational ones (e.g., Bisiach, 1993). It is extremely difficult to disentangle the two accounts if one takes the view that the representation of the external world is separate from the attentional processes that operate on it. Whether the postulated representation is faulted (in that it lacks objects to the left side) or the attentional processes are faulted (in that they fail to cover the left side of an intact representation) will inevitably remain confounded. Neglect can occur in a purely 'imaginal' domain as first shown by the well known study of Bisiach & Luzzatti (1978) in which patients were asked to describe a cathedral square from a certain viewpoint and neglected details to the left of this imagined viewpoint. Although imaginal neglect was always presumed to be accompanied by neglect of actually viewed scenes recent reports suggest that imaginal and perceptual neglect are fully dissociable (Guariglia, Padovani, Pantano & Pizzamiglio, 1993; Marshall & Halligan, 1993). Again what this tells us about the role of attention and representation in the disorder is not clear. Some patients who appear to show no impairment in reporting left objects in a scene may nonetheless fail to report these objects when required to remember the scene - a deficit that could equally well arise from a failure to direct attention to the left side of visual images as from a failure to generate the left side objects in the image. As Bisiach (1993) argues the two processes are probably falsely separated and better understood as grouped together under the dynamics of representational activity itself.

2.5.1. Frames of reference in neglect.

As well as an imaginal - perceptual dimension, the disorder can be characterised according to the frame of reference within which left-neglected objects are determined as left, and according to the predominance of the impairment along a perceptuo-motor dimension. Both of these latter dimensions again reflect the range of visuo-motor transformations taking place in the parietal area. With regard to frames of reference neglect has been shown to operate on objects whose position is defined left relative to viewer, environment and object centred frames of reference. For instance Farah, Brunn, Wong, Wallace & Carpenter (1990) asked patients to report letters distributed inside outline drawings of common objects. They found that patients typically failed to report letters to the left of their line of sight as well as to the left of the display as a whole - showing evidence of viewer and environment centred left neglect. They found no evidence for object centred effects. These authors argued that this evidence is consistent with the view that the frames of reference within which visual objects are represented is the major difference between the dorsal and ventral pathways. This view shares similarities to the distinction made between the two pathways by Goodale & Milner (1991) in as much as computing representations to guide actions involve the use of viewer centred representations of object properties.

The viewer centred - object centred distinction is likely to be too simplistic as a characterisation of the differences between the kind of representation in the two pathways. Object centred neglect has been shown to occur following lesions to the right parietal lobe. Driver & Halligan (1991) report a patient with severe left neglect who failed to discriminate shapes when the relevant features of the shape appeared in the non-neglected right side of space, but on the left side of the object relative to its object-centred principal axis. Similar results have been reported by Arguin & Bub (1993) concerning the neglect of stimuli which were left with respect to their position within a stimulus array, even though the complete array could be to the right side of the patient's line of sight. Thus, although less common, object centred neglect does occur and implicates the parietal areas in using more than viewer centred representations of object properties. Actions are executed by effector systems that can be broken down into components dealing with a specific aspect of prehension and sensitive to the specific object properties that affect that component. The frames of reference in which different object properties are represented are likely to reflect the effector systems that engage those properties during prehension (and during other visuo-motor tasks in general). As Jeannerod (1994) argues extracting the opposition space from an object probably requires the use of an object centred description - the hand shape required to grasp the object is more or less invariant with respect to its position and orientation taken with reference to the viewer. Furthermore, behavioural data indicate that, during manual reaching tasks, object properties such as location may be represented not simply in viewer centred frames but in frames centred on the effector used to execute a response (see Tipper, Lortie & Baylis, 1992). These authors found that interference effects of distractor objects were most pronounced when they were closest to the target object with reference to a co-ordinate frame centred on the hand of the subject, rather than on either retinal or environmental co-ordinate frames. The notion of viewer centred coding in the dorsal stream would perhaps be better construed by taking account of the diverse effector systems that, effectively, do the 'viewing'. Viewer centred coding can then be seen as a family of representational frameworks all of which share the common property that the spatial object properties are defined by reference to their own position or viewpoint.

2.5.2. Perceptual and motor neglect.

The many different frames of reference used to represent object properties reflects one aspect of the transformation of visual information into motor output that studies of neglect reveal. The disorder can also be characterised along a perceptuo-premotor continuum. At the perceptual end of this continuum neglect arises primarily from either an impaired representation of the left side of space (and/or the directing of attention to this area) whereas at the premotor end it arises mainly from an impairment in directing actions to the left side of space. The types of neglect can be distinguished by dissociating the direction of movement of a pointer from the direction of the action needed to move it in that direction. Patients with predominately perceptual neglect tend to ignore objects to the left of a display, regardless of the direction of hand movement needed to operate a pointer. In contrast, patients in which the disorder is predominately premotor fail to point to stimuli on the left when this requires also moving the pointer to the left. In contrast, in the dissociated condition where leftward arm movements result in rightward pointer movements and vice versa, patients typically neglect stimuli on the *right* of the display despite having unimpaired motor function (Bisiach, 1993). Thus the premotor form of the condition involves the neglect of leftward *movements* regardless of the position of the stimuli and not because of any physical inability to perform movements in that direction. The distinction between perceptual and premotor neglect is not necessarily stable in individual subjects. Bisiach (1993) reports a preliminary study in which neglect patients were examined on a modified version of a line cancellation task using reversing mirrors to dissociate the direction of hand movement from the visual location of the lines. Originally this task was used as a method of separating premotor and perceptual neglect (Tegner & Levander, 1991) and involved line crossing under normal and mirror reversed conditions - in the latter patients' hands as well as the stimulus lines appeared on the opposite side to their physical location. In the manipulation reported by Bisiach (1993) patients also had to initiate line crossing in the region that had just been neglected in the mirror reversed condition. Whilst some patients immediately revert back to neglecting this side of space there are also those whose neglect switches from premotor to perceptual under this spatial cueing. Thus a patient may initially fail to cancel lines that require moving the hand to the left regardless of where those lines are perceived. Following spatial prompting to the neglected side they then proceed to cancel lines on this side of space whilst now ignoring those lines in the previously attended region. At least in some cases, then, the action state of the patient has a dramatic effect on the predominance of perceptual or directional motor neglect. Even using mirror reversal techniques involves both a motor and a perceptual task, even though their relative directions can be dissociated. An alternative method of distinguishing between perceptual and motor (or input - output) components of neglect is to incorporate conditions in which patients make judgments that have no motor component. Reuter-Lorenz & Posner (1990) employed a line bisection task that could be undertaken either actively, by the patients themselves, (in which case they mark the centre of the lines) or passively, (in which case the patient determines when the experimenter's pen is at the centre of each line). Their patients all had right posterior parietal damage with characteristic left neglect. The lines were distributed on both the left and right sides of centrally placed sheets of paper and in the passive condition the experimenter began moving the pen from either the left or right side. Left neglect (rightward error in the estimation of the line's centre) was produced in both the active condition and in the passive condition when the experimenter began moving the pen from the right side. When the experimenter began moving the pen from the left no neglect was found. In addition they found no effect of hemispace (side of paper in which the lines were grouped). The magnitude of the patients' errors were always greater in the active condition implying that both premotor factors as well as perceptual ones entered into the observed effects. They found no evidence of any effect of hemispace and suggest that the direction of visual orienting may play as important a role in neglect as the representation of specific regions of space. The close link between perceptual-attentional and motor factors in neglect has also been observed in the monkey. In particular, a study by Rizzolatti, Gentilucci & Matelli (1985) showed that the lesions to brain areas known to control particular types of actions (such as reaching and grasping and orienting to stimuli) also produced neglect restricted to the region of space in which those actions take place. They found that covert attentional responses to contralesional stimuli in the space surrounding the body (peripersonal space) were neglected following lesions to areas 6 and 7b which control hand and arm movements. Conversely lesions to the frontal eye fields, which control visual orienting resulted in neglect restricted to stimuli in the far space. They interpret their results as inconsistent with the view that there is a 'master' centre for the control of attention located in the parietal lobes. Instead they argue that each area that controls a particular class of actions is also endowed with its own attentional mechanisms (importantly, the methods of testing for attentional impairments in this study were not confounded with the motor mechanisms needed to reveal them). If their interpretation is correct, (and the evidence is from association only, not dissociation or double dissociation), performing actions in a particular region of space involves attentional mechanisms dedicated to that spatial area. This makes sense if, as suggested by Stein (1992), one of the roles of attention is to control the kind of co-ordinate transformations that need, at least implicitly, to take place from retinal input to motor output. The significance of objects and events for action depends, in part, on their location with respect to the animal, and in particular with respect to the effector systems of the animal. Having attentional systems geared to facilitate visuo-motor transformations, relevant to the kinds of action that can be performed in the attended space, makes ecological sense.

The patterns of impairment associated with visual neglect bear on many aspects of spatial representation, attention and visuo-motor coordination. Although the evidence is full of interpretational difficulties, not the least of which being the impossibility of determining precise information about cortical damage in human subjects, they nonetheless do point to the multiple levels of representation involved in visuospatial processing and to the integrated and massively parallel, nature of perceptual and motor representations. The phenomenon cannot be accounted for by assuming it arises from the disruption of a specific region of a single representation of external space, or from a lack of attention to that area. How external space, and the objects within it, are represented reflects the fact that the primary purpose of those representations is to co-ordinate motor activity. Doing this requires the use of multiple levels of representation of spatial and object properties that reflect the different co-ordinate systems of the effectors of the organism. As is evident from what is known about the neurophysiology of visuospatial and motor processing in the parietal and motor areas the transformation of visual to motor information does not take place in discrete serial steps.

The evidence from both neuropsychological studies and behavioural studies indicates that the two major functions of vision - recognising objects and events and guiding behaviour - are functionally distinct. The dorsal and ventral systems, although not anatomically isolated, nonetheless process visual information independently such that the outputs of the two systems can be dissociated by cortical lesions and sensitive behavioural measures in normal subjects. It is also apparent that not all behaviour can be guided by dorsal processing alone, but requires a certain degree of ventral input. The extent to which such processing remains functionally separate in normal subjects has yet to be fully determined. However, the neuropsychological evidence indicates that object properties related to the distal components of prehension are still dissociable, contradicting any notion that ventral input is necessary for the representation of these object properties and the computation of the wrist and finger movements associated with them. In the next section the neurophysiology of the dorsal system and the motor system it projects to is examined with particular emphasis on the integration of visual and motor functions. This integration is of special importance for the theoretical position adopted here. Understanding that representing the 'visual' properties of an object is a process that is not distinct from representing components of the actions that the object affords is the key point.

2.6. Neurophysiology of the parietal and motor areas

2.6.1. Spatial coding in the parietal cortex.

The dorsal processing system projects mainly to the posterior parietal lobe, which in turn projects to the motor and premotor areas. The area receives input from multiple sensory systems, vision being only one of these, and is often referred to as a sensory association area. Spatial response properties of cells in this area, particularly area 7a, have been one of the most extensively studied characteristics. Receptive field sizes tend to be large which enables highly accurate representations of stimulus locations to be achieved through 'coarse coding' (Rumelhart & McClelland, 1986). In their model of the spatial coding of stimuli by area 7a neurons, Zipser & Andersen (1988) found target positions to be represented in head centred space, although such a coding scheme is only implicit in their model. Physiological recordings from this area indicate three types of cells important in the maintenance of a head centred representation of stimuli. These comprise those responsive to the position of the stimulus on the retina, those responsive to eye position and those whose response to visual stimulation was a function of the position of the stimulus on the retina, but modulated by eye position. It is this latter class of cells that can be said to represent stimulus location in head centred space. As the authors point out the output of any computation of head centred location is probably the actual implementation of a motor command to perform a movement to the object. Head-centred coding, by itself, only provides sufficient information for orienting the head to the stimulus. Other actions require other coding schemes that, for instance, take into account the position of the head with respect to the effector. Because of the many different effector systems that can be involved in potential actions, each having their own reference frame, it remains questionable as to whether any single coding scheme is applicable to visuo-motor behaviour in general. This point is made by Stein (1992) in describing the posterior parietal cortex's (PPC) role in the representation of external space. Stein argues that the PPC may best be understood as a distributed system of reference frame transformations each specific to a particular effector system. Thus no 'absolute' map of external space needs to exist and would be computationally wasteful. Depending on the actions required by the organism all that is required is that retinal information be transformed to motor output. In this regard the neurons modeled by Zipser & Andersen (1988) can perhaps best be understood as being part of a system of transformations for a set of motor behaviours, rather than as being involved in the explicit representation of stimulus location within a particular frame of reference. For many actions a head-centred representation of target location is a necessary prerequisite for accurate engagement, but it is only a component part of the co-ordinate transformations that need to be made. No doubt other groups of cells could be found whose response properties were sensitive to target position with respect to the hand or arm but modulated by head position, thereby fulfilling the role of an ‘arm or hand’ centred representation. The point is that such representational schemes are not necessarily explicit spatial representations of stimulus positions - this is a description too easily attributed to them given our knowledge of the computational steps required. Rather they may be an integral part of a visuo-motor transformation specific to an effector. As such many of their response properties may well coincide with those required in building a model of spatial location within a particular reference frame, but it is probably misleading to equate this with their primary function. Instead these properties reflect the nature of the visuo-motor transformations required in bringing any effector to a target.

As well as having large receptive fields the cells in area 7a also exhibit a bias toward the lower visual field. Previc (1990) has argued that specialisation within the dorsal and ventral streams for processing in the lower and upper visual field is an important functional difference between the two pathways. Such a preference is consistent with the role of the dorsal pathway in mediating visually guided behaviour as almost all visually guided behaviour such as reaching and manipulating objects takes place in the lower visual field. Not only do the cells in the dorsal pathway exhibit a bias toward the lower visual field but also for processing in the 'near space' as evidenced by more global processing properties and a preference for near disparities. A visually guided behaviour such as prehension requires efficient global processing. During reaching, for example, the hands and arms move toward the fixated object within the lower visual field. Almost for the whole of the movement they will subtend large visual angles and be at near (uncrossed) disparities. Global processing properties and a preference for near disparities thus aids the accurate monitoring of limb position during reaching. Not surprisingly the transport component of prehension depends largely on peripheral vision, whereas the manipulation component on foveal vision (Sivak & MacKenzie, 1990). Precise visual information about limb position *during* reaching is probably not required, however, as the ‘open loop’ studies by Jeannerod (1981, 1984) make clear. Where an advantage for accurate localisation of limb position is important, however, is in providing accurate information about the starting position of the limbs immediately before a movement is initiated as this enables proprioceptive information about limb position to be recalibrated (Jeannerod, 1986).

2.6.2. Visuo-motor coding.

The relation between the representation of spatial and other object properties in the parietal areas and the representation of motor properties in the premotor and motor areas is highly distributed. It is certainly not the case that a serial process of converting spatial stimulus attributes to motor commands takes place from posterior parietal cortex to the motor cortex. Whilst cells responsive to 'visual' aspects of the stimulus are more common in the parietal areas and those primarily sensitive to 'motor' properties of the forthcoming response are more common in the motor and pre-motor areas, both areas share populations of cells sensitive to both motor and visual properties. Furthermore both areas contain cells whose response properties are determined by the combined relation between visual and motor properties. Taira, Mine, Georgopoulos, Murata & Sakata (1990) studied the response properties of area 7a cells in the monkey. They found cells specifically related to a particular class of action. Importantly this class of cells were not related to reaching to the location of the object but to the hand shape required to grasp it. They found three major groups of cells. The first they termed 'motor dominant' and consisted in cells that were sensitive mainly to manipulating the object and were equally activated when responses were carried out in the dark as in the light. The second they termed 'visual dominant' consisting in cells that responded during visual fixation of the object and its manipulation in the light. The third group which they termed 'visual and motor' consisted in cells activated by the manipulation of the object in the light, (but not by its mere fixation), and showing a marked decrease in activity when the object was manipulated in the dark. This group was thus neither sensitive to visual fixation or manipulation alone but required a visual and motor input to be activated. Many of these cells were also selective for the hand shape required to grasp the object and to its orientation. A group of cells with very similar properties was recorded by Rizzolatti, Carmada, Fogassi, Gentililucci, Luppino & Matelli (1988) in inferior area 6 (area F5) of the premotor cortex of the macaque monkey (see also Rizzolatti, Gentilucci, Fogassi, Luppino, Matelli & Ponzoni-Maggi, 1987). They found that these neurons were selective for the type of hand shape involved in grasping an object such as whole hand prehension, grasping with the fingers, and for precision grips between the index finger and thumb. Many of these neurons were also activated by the fixation of the object and even when the animal observed the experimenter, or another animal, perform the action for which they were selective (Di Pelligrino, Fadiga, Fogassi, Gallese & Rizzolatti, 1992). As Jeannerod (1994) observes this property highlights their role in representing types of action independent of any actual intention to execute it. Varying the spatial location of the object had little effect on their response properties - the relationship was anchored to the grip type required to grasp the object, not where in space the object was. In contrast neurons in area F4 of inferior area 6, which code for proximal motor acts such as reaching, show response properties that depend on the position of the stimulus with respect to the body (Gentilucci et al., 1988). The authors suggest that these neurons form a vocabulary of motor acts as opposed to single movements - a proposal consistent with the view that the motor and premotor areas represent movement characteristics at a much higher level than the implementation of muscle commands (e.g. Georgopoulos, 1992). The precise role played by different populations of neurons sensitive to the same type of stimuli in coding reaching properties is difficult to assess. Sakata, Taira, Mine & Murata (1992) suggest that the parietal neurons may help to match the visual stimulus with the hand commands generated in the motor areas- a view consistent with the observation that many parietal neurons are activated *after* the activation of motor neurons with corresponding stimulus sensitivity. The most important point is that the way visual stimuli are coded would appear to involve representations that reflect the motor acts that can be elicited toward them. That many of these act-related neurons are activated simply by the sight of the stimuli gives plausibility to the idea that certain actions may be activated without intentions to perform the action.

Furthermore, the finding that groups of cells code for a vocabulary of the motor acts that make up a complete action, such as reaching and grasping, implies that the separate *components* of afforded actions may be represented simultaneously and in parallel, despite the necessity of their serial execution during an actual action. It must be stressed, however, that the tasks involved in the preceding studies all involved explicit actions at some stage. Taken alone, the data do not implicate action potentiation but do provide grounds for its neurological plausibility.

2.6.3. Neuronal coding of the direction of forthcoming movement

The neuronal population code for the direction of forthcoming movement has been one of the most successfully studied neural codes for reaching actions. The properties of such codes shed important insights on the way motor information is represented and transformed during goal directed acts. Georgopoulos, Schwartz & Ketner (1986) describe how the three dimensional movement of the arm can be uniquely determined by the vector sum of populations of cells each having a preferred directional sensitivity. Individual cells in the motor cortex are broadly tuned to the direction of movement approximating a cosine tuning function about their individual preferred direction - the cells activity is approximately a linear function of the cosine of the angle between the cell's preferred direction and the actual direction of movement (Georgopoulos, Taira & Lukashin, 1993). Thus the activity of each cell, as measured by impulse frequency, is maximum at the preferred direction and declines according to a cosine function as the actual movement moves away from this direction. The direction of movement of the arm can be accurately predicted, however, by taking the vector sum (where the length of each vector is the activity level of the cell) of the whole population of cells whose activity changes with the arm movement. Population codes are a robust representation of movement direction as randomly reducing the number of cells contributing to the code results in only a limited decrease in the accuracy of the predicted direction of movement. Accuracy is only seriously affected when the number of contributing cells is fewer than about 100 (Georgopoulos, 1989), a property which is dependent on the fact that individual cells preferred directions are distributed uniformly through space. Population codes for the direction of forthcoming movement can be found in both motor and parietal areas. An important property of these codes is that they do not relate to muscle activation but to the direction of the movement independent of the means by which it is implemented. In fact, the primary motor cortex itself, although originally presumed to function as a muscle controller, contains relatively few cells directly related to muscle activation (Georgopoulos, 1991). When reaching movements are carried out in different parts of the space surrounding the body, but in the same direction, cells' individual preferred directions change. This change in preferred direction corresponds to the change in rotation about the shoulder joint. The overall population code, however remains unaffected as the vector sum remains the same (Caminiti et al., 1992). This supports the view that the direction of reaching movements is coded in a shoulder based co-ordinate space consistent with psychophysical measurements in humans (Flanders, Tilery & Soechting, 1992). Temporal properties of population codes also suggest that higher level representations of movement parameters are represented in the motor areas. The population vector provides a reliable indicator of forthcoming movement direction during 'instructed delay periods' in which subjects know what the forthcoming movement will be but must wait until a go signal is delivered. Interestingly, in conditions that require animals to make a movement at a fixed angle away from the target, the population vector computed in the motor cortex can be seen to rotate during the delay period - initially pointing in the direction of the stimulus and then successively shifting from this direction to that required by the instructions (Georgopoulos, Lurito, Petrides, Schwartz & Massey, 1989). In this case, despite no explicit intention to direct a movement to the location of the target, the latter is nonetheless represented in the *motor* population code.

The activation of actual muscles is largely carried out by sub cortical spinal tract neurons, although even here there is no direct relation between the activity of single cells and muscle activation (Fetz, 1992). The representation of movement parameters by the motor cortex appears to be carried out at levels much higher than that of muscle activation. In this respect it remains more similar to the parietal cortex, the difference between the two areas being one of emphasis rather than major functional segregation. In general population codes present in parietal cortex (area 5) tend to be less sensitive to external force conditions. Thus if a reach has to be made to a location under conditions in which the arm has an external force applied, the trajectory, but not the muscle commands necessary to implement it, remains the same as when no external forces are applied. The fact that many parietal area 5 population codes remain insensitive to the external forces applied (load conditions) implies that they are coding movement parameters at a kinematic rather than dynamic level. In the motor areas population codes tend to be more sensitive to load conditions and can be thought of as relating to the dynamics of the movement. However even in the motor areas a large proportion of cells can be found that are far removed from muscle activation and dynamic properties of the movement (Kalaska, Crammond, Cohen, Prud'homme & Hyde, 1992). Alexander & Crutcher (1990a) trained monkeys to move a visual cursor by arm movements about the elbow. Even when the direction of elbow movement was dissociated from that of the visual cursor target (by using a pivot between the cursor and the hand) over 78 % of the cells related to movement preparation in the motor cortex, supplementary motor area and globus pallidus remained insensitive to these load conditions and only sensitive to the direction of movement of the cursor. Thus the notion of the motor cortex as intimately related to muscle activation is a gross oversimplification. Furthermore, relations between the activation of muscles and motor cortical cells are highly variable over time, even within individual animals. In the primary motor cortex individual cells activate many muscles and any particular muscle may be activated by stimulation at several disparate sites. Following nerve transection muscle patterns in the motor cortex can reorganise themselves in as little as fifteen minutes (Sanes & Donoghue, 1992). This adaptability has, of course great advantages in a biological system and is, in fact, a requirement for successful motor behaviour. The properties of the muscle plant in the limbs change slowly with development and aging, as well as rapidly following injury. Thus the ability for motor commands to engage different muscle sets with different forces to achieve a constant trajectory is a necessary property of a system whose effectors do not maintain constant output characteristics.

2.6.4. Problems with the interpretation of neurophysiological recordings.

Although neurophysiological recording studies offer significant insights into the underlying mechanisms involved in visually guided reaching, attributing causal roles to the putative neurological representations of movement parameters is highly problematic. At best such studies serve to indicate the highly distributed nature of visuo-motor processing and the integration of perceptual and motor processing. What is clear is that there is no neat parcellation of the formal computational steps required in a reaching movement into different functional brain areas. Similarly, although the necessary steps involved in computing a reaching movement have a serial order (Hildreth & Hollerbach, 1987) there is no correspondingly serial activation of different types of representations in the brain. Despite this there remain clear functionally and topographically separate circuits for different body parts such as the arms, legs and face (Alexander, 1992). Within each 'motor circuit', however, the separate processing stages are not clearly separable. For instance the kinematics of a reaching movement need to be computed before the dynamics can be determined, but there is no evidence from recording studies that neural populations coding kinematic properties are activated before those coding dynamic properties (Kalaska et al., 1992). Multiple representations of the same movement parameters are activated in parallel across multiple brain areas and representations of different parameters co-exist within individual brain areas. Detailed knowledge of how the brain successfully carries out reaching movements is largely unknown. Fetz (1992) argues that because individual cells and populations of cells can be correlated with different aspects of reaching movements does not substantiate the causal role played by such cells or populations of cells in bringing the movement about. Moreover in most recording studies a large proportion of cells show no modification, or only an uninterpretable modification, during reaching. These are ignored in most studies resulting in the false impression that explicit coding of movement parameters can be found in various motor neuron populations. Neurons with highly complex relations to movement parameters may play a significant part in the generation of motor output. Much criticism of the interpretation of both single cell and population recordings comes from insights gained from connectionist models. Thus it is the connectivity and not simply the activation level of various cells that determine the output function of any neural ensemble, and correlating an (arbitrarily determined) weighted sum of cell activations with a movement parameter does not guarantee that the function of those cells is to code that parameter (Fetz, 1992). By the same token even greater caution must be taken when interpreting the response properties of single cells by simple correlation of their activation levels with particular motor outputs, given that such cells can be considered analogous to hidden units within a large network (Robinson, 1992). Without a complete understanding of the input and output relations of single cells it is not possible to infer their representational role from their response properties. A good example from the connectionist literature is Lehky & Sejnowski's (1988) model for deriving shape from shading. They found that the pattern of activations that emerged in the hidden layers of their network model were selectively sensitive to oriented bars. As such they could too easily be interpreted as serving the function of detecting edges at specific orientations. The nature of their model, however, shows this conclusion to be false - the function of such cells depends not just on the pattern of inputs that activate them but also on their output connections.

2.7. Conclusions

Taken together, neurophysiological and neuropsychological data can perhaps best be described as providing quite general and imprecise, but nonetheless important, insights into the way we use visual information to prepare and guide actions. The empirical data from both research areas has been collected from goal directed tasks. Actions are, of course, goal directed. The aim of a reaching movement, for example, is to achieve a successful grasp of an object. Unfortunately this usually leads to the problem of visually guided action being framed as a transformation problem that begins with a purely 'visual' representation of the environment. Only when an intention to act has been formed is the transformation from visual to motor undertaken. This transformation is seen to depend on the existence of a *goal* object (in the case of reaching tasks). What is clear from work on the human and primate visuo-motor system is that this transformation is carried out in a massively parallel manner and involves multiple representations of visual and motor properties across many different cortical regions. What is not clear, however, is the extent to which such a transformation is only performed when a decision to act toward an object has been made. Obviously the complete process is not performed, in normal subjects, without an intention being present - for we would be completely stimulus driven if this were the case. This does not imply, however, that no elements of this transformation are present until an intention is formed. In fact the notion that the way visually guided action is planned, initiated and executed as being a *transformation* from visual input to motor output is restrictive and not necessarily the right framework within which to analyse the process. Such a formulation tends to encourage the false separation of visual and motor representations and, in so doing, assumes the role of intermediate representations to be products of this (intention initiated) transformation rather than an integral part of the initial representation of the visual object itself. Put differently, while it is apparent that in any visually guided act a visual to motor transformation takes place, of necessity, it is not necessarily the case that the representations used as the start point for that transformation only include purely 'visual' components. It is plausible that the start point of this transformation process is further down line and that the representation of a visual scene already includes visuo-motor components.

It is of interest to note here the results of a study by Goldberg & Seagraves (1987) on attentional mechanisms in the monkey, in which they report evidence that the process by which saccades are generated to a single target amongst many, involves the selection of already existing simultaneous (and therefore conflicting) motor signals. Motor signals do not wait for a stimulus to be selected as a target, rather the attentional mechanism (motor attention in their terms) that results in a saccade selects one motor signal from a multitude of pre-existing signals automatically generated by the visual stimuli in the environment. The extent to which such a process applies to higher level acts remains open and is the main theme of the experimental work presented in subsequent chapters. Taken alone, neurophysiological and neuropsychological evidence does more to highlight the number of possible mechanisms that the nervous system could employ to carry out visuo-motor transformations rather than to constrain them. This applies equally to the actual transformations that take place as well as to the representational schemes that they operate upon. Given that the visual system's primary function is to aid navigation through the world it would not be surprising that the way objects are represented includes motor components. The location and size of an object, for example, must be specified relative to the organism doing the viewing if it is to be a useful representation. This point has long been recognised by the ecological tradition in perception and action (Gibson, 1979; Turvey, 1990, 1992; Turvey & Carello 1986), although that approach is not representational. Ecologically motivated studies of catching actions, for example, suggest that actors know not where the ball will be but only how to get their hands to that position (Peper, Bootsma, Mestre & Bakker, 1994; McLeod & Dienes, 1996). From a representational framework this idea can be expressed as the notion that a representation of an object includes the coding of some of its affordances. This is not the same as merely suggesting that the object properties that determine its affordances are represented when we view an object. What makes this the coding of affordances rather than the coding of the object properties themselves, is the way they are represented. The location, size and orientation of an object are the primary determinants of its affordances (higher level affordances, that depend on knowledge of object function can, of course, be proposed but are here assumed to be secondary to those relating to its physical parameters). These properties could be represented only in visuospatial terms - without any reference to the motor system. To represent them as affordances, however, implies that they be represented with reference to the action system of the organism. A possible mechanism whereby this could be achieved is by engaging the visuo-motor (rather than just the visual) system in their representation. Representing an object's location would then involve the partial activation of the motor programs needed to transport the hand to that location. Similarly representing the size and orientation of the object would involve the motor systems involved in hand preshaping and wrist orienting. If such a scheme is to work there would obviously need to be constraints on when such properties were so coded. At the output end of visuo-motor activity a single action has to be selected (Allport, 1987). Exactly where along the continuum of visuo-motor processing the selection for a single action takes place would be a matter for empirical investigation. Undoubtedly attentional processes would likely play a major part. Before that point is reached, however, multiple representations of visuo-motor patterns associated with object properties could coexist. The neurophysiology of the visuo-motor system certainly does not rule out this possibility. Moreover it also fails to rule out the possibility that such representations could be activated before any explicit intention to make a movement has been formed. The following chapter focuses on an empirical methodology capable of examining some of the predictions following from this proposal.

3. Chapter 3: Stimulus-Response Compatibility and Action Potentiation.

3.1. Introduction

Choice reaction time paradigms have been used to investigate many different psychological processes. The Stimulus-response Compatibility (SRC) paradigm focuses on the relation between responses and the stimulus properties that signal them. It is well known that certain pairings of stimuli to responses result in faster response times and lower error rates than less 'compatible' mappings. Potentially the variety of stimulus-response (S-R) relations that can be investigated using this conceptually simple, choice reaction time framework, is extensive, and yet most research on SRC has used abstract and impoverished stimuli and responses. An interest in the relation between perception and action has only recently been taken up in the SRC approach. For the purposes of investigating the proposals set out at the end of the last chapter, the SRC methodology can supply a useful experimental framework. Of particular relevance is a branch of SRC research devoted to the effects of irrelevant stimulus properties on the speed with which responses are executed.

3.2. The SRC paradigm

In typical SRC tasks subjects make choice reaction time responses cued by a particular stimulus property such as location or colour. The task can be defined by three major variables: the stimulus set, the response set and the mapping rule that determines the relationship between stimulus properties and the responses to be executed. The stimulus set includes all the properties of the stimuli that can vary from trial to trial. Only one such property or dimension, such as location or colour, is relevant to the choice of response. The response set likewise includes all the properties of the response that may vary across trials. Again, only one varying property or dimension of the response is cued by the relevant stimulus property. Thus subjects may be required to press a red response key when the stimulus is on the right and a green key when the stimulus is on the left. A wide range of possible SRC arrangements are made possible by varying the number of elements within, and the similarity between, the stimulus and response sets as well as by varying the mapping rules that assign stimulus properties to particular responses. Whenever there is a relation between stimuli and response sets, mapping rules that are congruent produce faster reaction times than those which are not. A simple example is that assigning left stimuli to left responses and right stimuli to right responses result in faster response times than the opposite, incongruent, mapping. The stimuli and response sets invariably will have properties other than those that take part in the mapping rule. Such *irrelevant* stimulus and response properties can have important effects on reaction time, especially when they are common to both sets. To take a simple example, a (congruent) mapping rule might assign a red response key to a red stimulus and green key to green stimulus. The stimuli and responses might also share the property of being located on the left and right of the body midline. This location dimension, although having no relevance to the choice of response, nonetheless can exert powerful effects on the ease with which the correct response is initiated. Regardless of the mapping rule, a robust finding is that congruence between the location of the cued response and the position of the stimulus results in faster reaction times than when the two locations do not correspond. In fact this particular example, in which stimuli and responses share an irrelevant spatial dimension, is itself a branch of SRC that has received considerable attention and is known as the 'Simon effect', after Simon & Ruddell (1967). The Simon paradigm is of special relevance to the experimental work described later on, and forms the basis around which SRC is discussed below. First, however, it is worth examining in detail one of the most prominent models of SRC - Kornblum, Hasbroucq & Osman's (1990) Dimensional Overlap model, as it provides one of the best classifications of SRC tasks, based on the relations between dimensions of the stimulus and response sets in the experimental arrangement.

3.2.1. Dimensional Overlap in SRC Tasks

Dimensional Overlap

Kornblum et al. (1990) have provided an extensive taxonomy of SRC tasks using the notion of dimensional overlap (DO). The authors propose that the stimulus and response sets in any SRC arrangement can be regarded as being composed of categories whose relational structure is defined across the dimensions or attributes that they possess. In typical SRC experiments this is quite evident, as the stimuli are both simple and abstract, and vary across relatively few dimensions such as colour, location, or shape. DO refers to the similarity relations that obtain between the various dimensions of the stimulus and response sets. DO may exist between dimensions of the stimulus set, the response set and between the two. Thus if the stimulus set consists of coloured lights, appearing in either left or right spatial locations, and the responses are simple left-right key presses, DO between the stimulus and response sets is present on account of their shared spatial dimension. A difficulty which immediately springs to mind, and of which the authors are aware, is that of determining the degree to which any two dimensions overlap. DO is a matter of degree. It obviously exists in a one to one manner when, for example, stimuli and responses both consist of matching red and green colours, and also in the case of red and green coloured stimuli and, say, orange and blue responses. A necessary requirement is that a homomorphic relation exists between the two categories such that a mapping exists between them that preserves the internal structure of both.

The dimensions across which this relation holds do not need to be of the same modality. Kornblum et al. (1990, p.259) cite a study by Marks (1987) to illustrate a case of stimulus-

stimulus DO occurring across auditory and visual modalities. Here subjects had to perform a discrimination task of auditory, tactile and visual stimuli. This discrimination was enhanced when the dimensions of each of the stimulus modes corresponded. Thus discriminations were faster if high pitched stimuli were paired with bright lights and slower if paired with dim lights. Whenever there is DO across stimulus and response dimensions defined in the mapping rule, congruent and incongruent mappings are made possible. Although the concept of DO has problems, especially with regard to its explanatory power, it does provide a framework within which to classify SRC arrangements. Kornblum et al. (1990) originally classified SRC arrangements according to the existence of DO among the relevant and irrelevant dimensions of the stimulus and response sets. A later classification also included stimulus-stimulus (S-S) dimensions (see Kornblum, 1994). Systematically varying the existence of DO between stimulus-stimulus and stimulus-response dimensions produces eight possible SRC arrangements (see Table 3.1). These range from those in which none of the stimulus or response dimensions have any overlap to those in which DO is present in the S-S and both the relevant and irrelevant S-R dimensions. The authors point out that this latter type of SRC arrangement corresponds to the classic Stroop task.

Table 3.1. A taxonomy of Stimulus-Response ensembles derived from the Dimensional Overlap model. (Reproduced from Kornblum & Lee, 1994). Yes/no entries refer to the existence or not of dimensional overlap.

	Overlapping dimensions			Examples		
	S-R dimensions			Stimulus sets		
Ensemble Type	Relevant	Irrelevant	S-S dimensions	Relevant	Irrelevant	Response sets
1	no	no	no	colours	shapes	digit names
2	yes	no	no	digits	colours	digit names
3	no	yes	no	colours	digits	digit names
4	no	no	yes	colours	colour words	digit names
5	yes	yes	no	colours	position (left-right)	key press (left-right)
6	yes	no	yes	position	colours and colour words	keypress (left-right)
7	no	yes	yes	colours	colour words/ position (left-right)	key press (left-right)
8	yes	yes	yes	colours	colour words	colour names

Kornblum et al.'s (1990) model of SRC has two major components - representational and processing aspects. Dimensional overlap constitutes the representational component whereas the mapping instruction given to the subject constitutes the processing component. A central tenet of the processing assumed to take place is the *automatic* nature of response activation under conditions where DO exists between stimulus and response sets. If no DO exists between the two sets then no particular mapping rule should offer any advantage. In this case there is no relation between the stimulus and response sets and the correct response must be identified by a search through the list of S-R relations defined by the mapping rule (see Hasbroucq, Guiard & Ottomani, 1990).

The existence of DO between the stimulus and response sets is a necessary requirement for *congruent* and *incongruent* mappings. Thus if both stimuli and responses share a common dimension (the degree to which this dimension is common being a continuous rather than all or none property), with both dimensions being relevant, then the congruent mapping will assign a response that matches the value of the stimulus, whereas the incongruent mapping will assign a non matching response. If both relevant stimulus and response dimensions are left right location for example, a congruent mapping rule will assign left responses to left stimuli and right responses to right stimuli whereas the reverse assignment will hold for the incongruent mapping. The DO model assumes that whatever the actual mapping rule, the presentation of the stimulus under conditions of S-R overlap will result in the automatic activation of the response congruent with the stimulus. If, as in the case of a congruent mapping, this automatically activated response corresponds to the correct response, a verification process takes place and the response is executed with little delay. On the other hand, if the automatically activated response is not the same as the responses required from the mapping rule, it must be aborted and the correct response activated, resulting in a reaction time cost. The overlapping property of the stimulus thus acts in a similar manner to a valid or invalid prime in a standard priming task (Kornblum et al. 1990, p.260) and the automatic activation of any response codes depends on the existence of DO.

A further consequence of the existence of DO between the stimulus and response sets is that, even in the case of an incongruent mapping rule, it is still possible to derive the correct response by a rule that makes the effect of the number of alternatives redundant. Thus if the relevant S-R dimensions in a three choice SRC task are colour, and the mappings are white stimulus - black response, red stimulus - green response, blue stimulus - yellow response, it can be seen that this incongruent mapping nonetheless lends itself to a rule rather than an exhaustive search through the list of S-R pairs (Hasbroucq, Guiard & Ottomani, 1990). The automatic nature of response activation when DO exists also means that stimulus dimensions *not* relevant to response determination will activate corresponding responses that will facilitate or interfere with the activation of the actual response required by the mapping rule. Before going on to examine spatial compatibility effects in general and the Simon effect in particular, a brief outline of the major SRC effects is given in the light of the classification of SRC arrangements described above.

Whenever stimulus and response sets have DO on the relevant dimension (i.e. that specified by the mapping rule) the congruent mapping produces faster reaction times than the incongruent mapping. The greater the dimensional overlap, the greater the degree to which the congruent mapping offers a reaction time advantage. Decreasing the amount of SRC either by changing from a congruent to incongruent mapping, or by reducing the amount of DO present, results in an increase in the reaction time cost associated with increasing the number of response alternatives. For example a stimulus-response set with a large degree of overlap could consist of three identical colours of stimuli and responses, pressing a red key given a red stimulus and so on. Increasing the number of S-R pairs would have very little effect on the speed with which responses were executed. In contrast if the degree of overlap was less, for instance matching stimulus loudness to responses defined by size, any increase in the number of S-R pairs would have a much greater effect on processing time. This effect would be most extreme when the S-R relations were completely arbitrary. Thus by decreasing the possibility of deriving the correct response from a *function* of the stimulus property, subjects are forced to adopt a search strategy which necessarily takes longer the greater the number of possible S-R pairs. Finally, the effect of DO on reaction times to execute the correct response when it exists between an irrelevant stimulus dimension and the relevant response dimension is similar to its effects when it arises from the relevant stimulus dimension.

Problems with dimensional overlap

The major difficulty with the Dimensional overlap model arises from the inability to determine, *a priori,* the degree of overlap between any two stimulus and response properties. Kornblum et al. (1990) argue that the possibility of obtaining a mapping effect is dependent on there being DO between the stimulus and response dimensions specified in the mapping rule. Because DO itself is a matter of degree, this can lead to a certain circularity in the explanation of mapping effects. Given that cross modal compatibility effects can be obtained both for stimulus-stimulus relations, as in the study by Marks (1987), as well as stimulus-response relations (e.g. Proctor, Dutta, Kelly & Weeks, 1994) the process by which DO produces its compatibility effects is unclear. According to the DO model, if overlap exists between the spatial locations of the stimuli and responses, a stimulus appearing on the left will automatically activate the left response code, regardless of whether the mapping rule was congruent (in which case this is the correct response) or incongruent. The role of DO in this case is easy to understand. But what happens when the stimulus and response dimensions both have a spatial (location) dimension but they are orthogonal as when top-bottom stimuli are assigned to left-right responses? At first one would be inclined to say that no DO exists (certainly not the sort that would result from a process of automatic response code activation). But compatibility effects of mapping do in fact obtain with these SRC arrangements, and therefore, according to the DO model this implies the existence of DO. No doubt an appeal to some sort of structural similarity could be made for the basis of DO in this case but it is hard to see how the *automatic* activation of a left response code, say, could arise from the presentation of a stimulus in the lower of two vertical locations. In fact the salient features model of SRC (Weeks and Proctor, 1990) handles this arrangement much better. This model, which can be described quite simply, attributes compatibility effects of mapping to the correspondence of the salient features in the stimulus and response sets. In the case of orthogonal dimensions such as vertically aligned stimuli and horizontally aligned responses, compatible mappings are those that pair the salient top position of the stimulus with the salient right position of the response and the less salient lower stimulus position with the less salient left response. As Kornblum & Lee (1995) argue, the salient features account can in fact be subsumed under the concept of DO, with saliency merely representing one aspect of structural similarity. Whilst the salient features account handles the compatibility effects of orthogonal S-R relations, and in particular, cross modal S-R relations, well, it does not apply to the irrelevant stimulus properties responsible for Simon type effects. Even if one accepts that the saliency of stimulus properties can play a part in the DO that exists between them, it is definitely not the sort that can be used to explain automatic response activation. A consequence of this is that DO cannot provide a unitary mechanism that underlies all compatibility effects - of both relevant and irrelevant dimensions. It also has a serious weakness in its inability to predict *a priori* whether or not DO exists in the first place. Because it is such a broadly defined term deciding whether or not S-R dimensions do overlap becomes increasingly difficult the further one moves from obvious physical correspondence to more abstract conceptual or structural correspondence. The model then has at its centre a circular definition of DO in that the latter's existence is determined by the existence of the compatibility effect it purports to explain.

3.2.2. Spatial compatibility and the Simon Effect.

Spatial compatibility

The Simon effect is a special case of spatial compatibility. With spatial compatibility proper, a spatial property of the stimulus set (typically left right location in terms of a particular frame of reference) cues a spatially located response (again typically left or right). The spatial properties of the stimulus and response sets are the relevant dimensions, and typical congruency effects of S-R mappings emerge (Nicoletti, Anzola, Luppino, Rizzolatti & Umiltà, 1982). The precise relation between the two can be systematically varied to determine exactly what kind of spatial congruence is needed for there to be a compatibility effect in the congruent mapping. The frame of reference within which both the stimulus and response locations are defined can be manipulated. In the simplest form of spatial SRC tasks, in which stimuli appear on the left or right of the body midline, with head and eyes centrally aligned, and the responses are at equivalent locations to the side of the body, all of the possible frames of reference are confounded. Umiltà and Liotti (1987) dissociated the relative left-right stimulus location from the egocentric left-right location as defined by the subjects' midline. Unimanual discriminative responses were made to stimuli that appeared on the left or right of the body midline. Two boxes were shown that both appeared on the right or left of the midline. At the same time, or after a delay of 500 msec, a small stimulus square could appear in one of the boxes and subjects had to respond to the *relative* left-right location of the stimulus in either a congruent (relative left stimulus-left response) or incongruent (relative left stimulus-right response) mapping. The arrangement constitutes a type 8 arrangement according to the taxonomy found in Kornblum (1994) although Umiltà & Liotti (1987) refer to it as type 2 arrangement[1]. The authors found compatibility effects only of the relevant relative location dimension and not of the irrelevant egocentric location dimension. In contrast to Kornblum et al. (1990) they argue that this suggests that only the relevant dimension exerts compatibility effects because it is subject to controlled processing. In a further experiment Umiltà & Liotti (1987) had subjects respond to the egocentric position of the stimulus whilst maintaining information about relative position. Again the authors found that only the relevant egocentric dimension now produced compatibility effects regardless of the delay condition (see Figure 3.1). This finding is quite unusual in that other studies of Spatial compatibility show that cases where both a relevant and irrelevant code are available simultaneously with the stimulus cue do produce compatibility effects. One might expect that in the delay condition, the precued spatial code (side in Experiment 1 and relative position in Experiment 2) would not exert a compatibility effect as any automatic activation would have had time to decay. However, one would expect such effects in the no delay condition. A possibility is that only one kind of spatial code is capable of being formed at a time, so that if both the relevant and irrelevant stimulus dimensions are spatial location, only one actually influences the responses. Umiltà & Liotti (1987) repeated their first two experiments but with left-right responses being determined by stimulus shape (square or rectangle). In both experiments side and relative stimulus position were irrelevant, the two repeated experiments differing merely in what irrelevant information was made available early in the delay condition.

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[1] Umiltà & Nicoletti 1990 actually say that the reason they classified this task as a type 2 arrangement was because of the lack of an effect for the irrelevant overlapping dimensions.

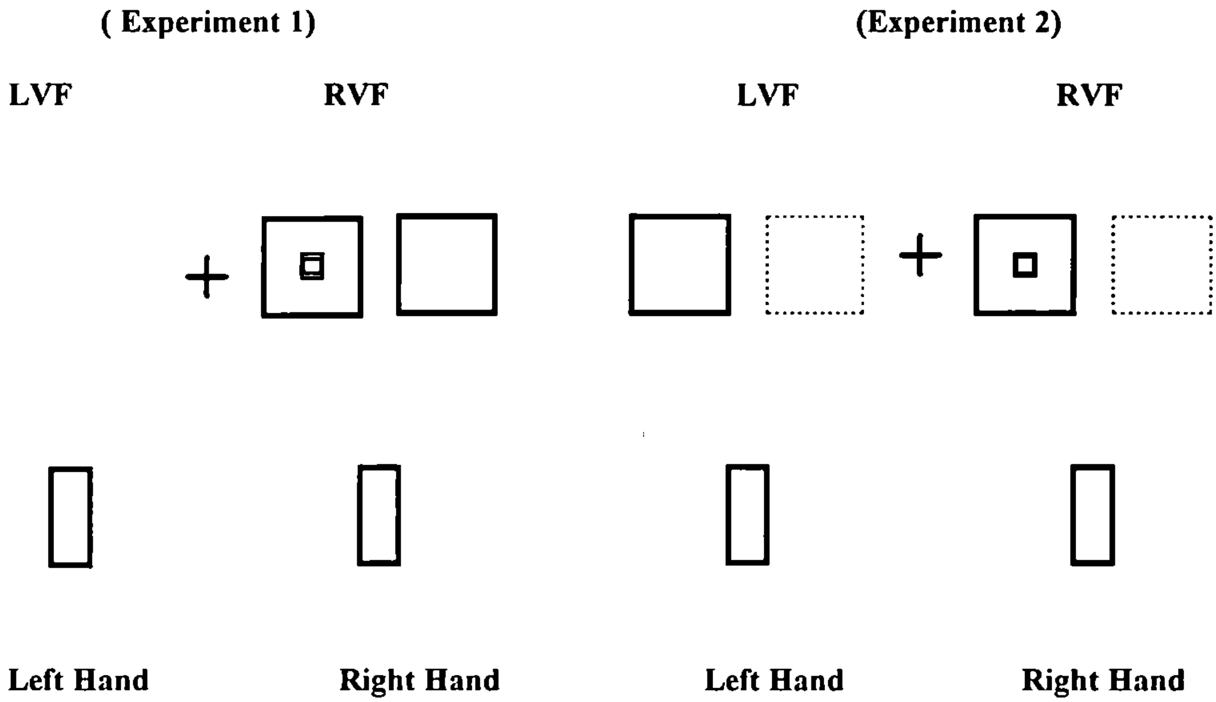

Figure 3.1. Schematic diagram of the stimulus-response arrangements in Umiltà & Liotti's (1987) experiments. RVF/LVF = left/right visual field. In Experiment 2 all four boxes appeared simultaneously but the imperative stimulus always appeared in the solid boxes.

Their results were unusual. In the delay conditions of both experiments a standard result obtained - there was a compatibility effect of the irrelevant spatial dimension that was made available at the onset of the stimulus cue, but none from the precued spatial dimension. Thus if information about egocentric side was precued but relative stimulus position was only made available with the appearance of the stimulus, responses were faster when the left-right relative position of the stimulus matched the left-right response cued by its shape. The same pattern occurred for egocentric side when this was made available with stimulus onset, and relative position was precued. In the no delay condition, however, both egocentric side and relative position were made available with stimulus onset. One would therefore expect both to exert compatibility effects. On the contrary, the authors found no compatibility effects for these spatial codes in either experiment. As the authors point out, the two codes would, of course have opposite values on half the trials and might therefore be expected to cancel each other out when the relative stimulus position was the opposite to its egocentric position. However there was no support for this in the pattern of results. If this were the case, the results would have shown a compatibility effect for those trials in which relative and egocentric codes coincided. Despite this Umiltà & Nicoletti (1990) maintain that these results might still result from mutual cancellation. One must suppose that this postulated mechanism involves a cancellation based not on opposing code values, but from some sort of interference that takes place when two codes are formed simultaneously. An explanation of the disappearance of the effect in this condition has been proposed by Stoffer (1991) and Stoffer & Yakin (1994) based on an attentional model of the Simon effect. These authors argue that the spatial code of the stimulus has its basis in attentional shifts. Left-right stimulus coding will only be present if the last movement of attention (before response determination) was a horizontal attention shift. In the simultaneous condition of Umiltà & Liotti's (1987) experiment Stoffer (1991, Stoffer & Yakin, 1994) argues that the last movement of attention was a zooming operation rather than a horizontal shift. Simultaneous presentation of the precue and imperative stimulus results initially in a horizontal attention shift to the configuration of both stimuli. The attentional reference frame is then reset to zero. To determine the required response an attentional zooming process must take place to the scale necessary to identify the imperative stimulus. On the assumption that the spatial reference frame is not altered by the zooming operation no directional code will be formed and therefore be available at the time of response determination. The role of attention in the formation of spatial codes in the Simon effect is important and is further examined below.

A similar series of experiments by Lamberts, Tavernier & d'Ydewalle (1992) failed to replicate Umiltà & Liotti's (1987) results. When the relative stimulus position was the relevant cue for the left-right response, these authors found additive compatibility effects of both this factor and the hemifield (manipulated by cueing subjects to a fixation point about which the possible stimulus left-right locations were defined). In this case there were three possible spatial codes, although that of hemispace was precued and failed to produce an effect, presumably for the same reasons as observed in Umiltà & Liotti's (1987) experiments. However, their manipulations meant that two of these codes were still available simultaneously, and the irrelevant spatial code did produce a compatibility effect. When all spatial codes were irrelevant to response determination (the latter being cued by stimulus shape) Lamberts et al. (1992) found additive effects of all three spatial codes including the precued hemispace. The finding of an effect for the precued (by 500 msec) hemispace is, as the authors note, quite surprising and they suggest a possible explanation based on the task requirements. Specifically, they argue, the fact that, in this instance, the left-right response was cued by stimulus shape meant that hemispace was less actively suppressed because it bore no relation to the response dimension. Thus when hemispace is irrelevant but similar to (i.e. still describable as left or right) subjects might actively suppress this information in order to lessen confusion with the relevant spatial cue. Whatever the true explanation this study represents the first demonstration of the additive effects of multiple spatial codes in S-R compatibility. The difference in the pattern of results between Umiltà & Liotti's and Lamberts et al.'s studies is difficult to reconcile. Some general conclusions, however, can be brought out regarding the properties of the stimuli that are important in producing spatial compatibility effects. First of all the absolute relation between stimulus position and response position does not appear to be critical. What matters for the compatibility relation is the match at the level of a cognitive code. Such a code can be based on a variety of reference frames which do not need to be the same as those used to code the response locations. The influence of such codes on spatially defined responses depends in part on their time course, as well as on the task constraints of SRC arrangements. As Umiltà & Liotti's (1987) and Lamberts et al.'s (1992) studies make clear, the conditions under which these potential codes actually enter into compatibility relations is not fully understood, although a convergence is apparent from more recent results on spatial compatibility discussed below.

Spatial compatibility is not restricted to the left-right dimension, although this is the most frequently studied, and appears to produce the strongest compatibility effects. If the stimuli and responses share a redundant spatial cue, such that they are either top right or bottom left, then the mapping rule given to subjects can be couched in terms of either dimension. In such paradigms the compatibility relations that emerge are restricted to, or much greater for, the left-right dimension (Umiltà & Nicoletti, 1990).

A problem with the coding account of SRC effects occurs when there is no overlap between the stimulus and response spatial dimensions. If the stimuli are vertically arranged and responses horizontal, compatibility effects still emerge. For instance Ladavas (1987), (see also Bauer & Miller, 1982), in a study using both left and right handers, found that there was a preference for a mapping that assigned up stimuli to the dominant (right or left) hand and down stimuli to the non-dominant hand. In this case there is no obvious overlap between the stimulus and response dimensions. The explanation Ladavas puts forward, based on the representation of the two hands along a vertical dimension, with the dominant hand assigned a higher position, is consistent with the more general framework of salient features coding in SRC (e.g. Reeve & Proctor, 1990 and discussed below). Other studies involving vertically oriented stimuli and horizontally oriented responses have shown that the 'preferred mapping' is quite unstable and can depend on the position of the effectors. Thus Michaels & Schilder (1991) found (using left or right movements of the index finger) that this top-right / bottom-left mapping was only the preferred mapping when responses were executed at the extreme rightmost position. The preference declined at more medial positions, was absent at a central location, and reversed at the extreme leftmost position, with responses now being carried out by the left index finger. They argue that the state of the action system strongly influences the particular compatibilities that emerge in any task although they do not offer a specific explanation of the actual preferences.

The effects of relative stimulus location are important in as much as they demonstrate that S-R compatibility does not depend on exact matches between the stimulus and response properties but on the activation of spatial codes with the same, or similar, values along a common dimension. The same is true for the relation of the response set itself. In the majority of studies bimanual responses are operated by the left and right hands operating left and right response keys. In such cases the position of the effectors is confounded with the position of the responses (as well as, in the case of the bimanual tasks their anatomical status). In essence, the spatial codes of the responses that appear to be critical for the compatibility relations mirror those of the stimuli. An established finding is that it is the position of the responses and not their left or right anatomical status that affects the compatibility. Left-right compatibility effects of similar magnitude to typical bimanual tasks occur when responses are executed by two fingers of a single hand (Katz, 1981). Furthermore, if a spatial SRC experiment is set up with the subjects' hands crossed so that the left hand commands the right response key and the right hand the left key, compatibility occurs when the left-right value of the stimulus matches the left-right value of the response location. Thus left responses are faster to left stimuli even though in this case the response must be produced by the right hand and vice versa for right responses executed by the left hand (Anzola, Bertoloni, Buchtel & Rizzolatti, 1977). Similarly, the relative positions of the response locations is sufficient for compatibility effects to be obtained. If the hands are crossed but both are to one side of the body midline, compatibility effects are still dependent on the relative left-right location of the responses (Nicoletti, Umiltà, & Ladavas, 1984). Furthermore, if the responses are operated by hand held extensions which can be crossed while the hands remain uncrossed and vice versa, response location again is the crucial factor in determining compatibility (Riggio, Gawryszewski & Umiltà, 1986). Whether any independent compatibility effects also arise from the egocentric rather than relative position of the responses, as is the case for stimulus dimensions, has yet to be determined (Umiltà & Nicoletti, 1990).

The Simon Effect

The Simon effect refers to the compatibility effect produced by an irrelevant spatial stimulus dimension. In the most simple case the relevant stimulus dimension is non-spatial, often colour or shape, whilst the responses are left or right key presses. The colour or shape of the stimulus cues whether a left or right response is to be made. The stimuli also have a spatial dimension that overlaps with the response dimension. If the stimuli appear to the right or left of fixation, then responses are faster when the position of the stimulus corresponds to the response location cued by shape or colour. Although the irrelevant variable of the stimulus that is used in Simon paradigms is most often location, the effect can arise, in principle, from any spatial overlap between an irrelevant stimulus dimension and response dimension. Most accounts of the effect assume that the irrelevant spatial property of the stimulus automatically produces a spatial code. Because responses share a spatial dimension, and also are presumed to be represented as a spatial *response* code, the spatial stimulus code is either congruent or incongruent with this response code. When the two codes are incongruent responses will be delayed compared to trials in which the two codes are congruent. Simon (1969) originally referred to the effect as arising from a natural tendency to orient towards the stimulus source. More recent accounts centre around the way the irrelevant spatial property of the stimulus is coded, although this process itself, shares similarities to Simon's original proposal in as much as attentional factors play an important part in this coding.

The dimensional overlap model (Kornblum et al., 1990; Kornblum 1994; Kornblum & Lee, 1995) locates the Simon effect at the stimulus-response translation stage. In their taxonomy the Simon effect occurs in a Type 3 ensemble in which there is no overlap between the relevant stimulus dimension and the response dimension but there is overlap between the irrelevant stimulus dimension and response dimension. If the stimuli possess two dimensions, such as shape and location, and the response one (location), three codes are potentially available on any given trial. The relevant (and non-spatial) stimulus code, the spatial response code that this stimulus attribute signals, and the irrelevant spatial code of the stimulus. Kornblum (1994) suggests that the mechanism whereby the Simon effect is generated actually arises from the automatic activation of a further *response* code that corresponds to the irrelevant stimulus property. It is activated *automatically* because of the presence of dimensional overlap. The correct response code is identified either by a list search, in the case where no rule based information about S-R mapping is made available, or by some rule applied to the stimulus property[2]. The automatically activated response is further presumed to be activated before the response code from the application of the rule or search process. On trials where both codes are congruent, the response is initiated

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[2] As Kornblum et al. (1990) make clear, in SRC arrangements where there are fewer than 3 response choices the difference between list search and rule based response identification is immaterial. When only two responses are possible any S-R mapping, no matter how arbitrary, can be reduced to a rule of the form if stimulus = x then make response a, else make response b. In set ups with more than 2 response alternatives the difference is apparent. Subjects will either have to search through a memorised list of S-R pairs, when no relation exists between stimuli and responses, or they can apply a rule that is independent of the number of response alternatives. It also should be noted that the application of a rule implies (according to Kornblum et al., 1990) the existence of DO between the relevant stimulus dimension and the response dimension (i.e. to cases other than those of type 3 ensembles, but which nonetheless may have components of the S-R relations similar to Simon tasks).

without delay whereas on trials where they differ it must first be aborted and the new response retrieved and programmed, resulting in increased reaction times.

The details of the S-R stages in Kornblum's model are shown in Figure 3.2. (reproduced from Kornblum et al., 1990). The model draws a major distinction between so called S-S and S-R consistency. The former concerns overlap that occurs on two stimulus dimensions as is the case of coloured colour word names, and the latter concerns the overlap between the response and stimulus dimensions. The Simon effect 'proper' concerns only cases where there is no S-S overlap but only S-R overlap on the irrelevant stimulus dimension, although compatibility effects produced by irrelevant spatial stimulus properties are often referred to as Simon effects regardless of the exact relation between the other stimulus and response properties. For present purposes it is the effect of irrelevant spatial stimulus properties that are important and not so much the particular type of SRC ensemble in which they are embedded. As can be seen from Figure 3.2 the DO model assumes that the stimulus identification stage results in the generation of a stimulus vector which consists of codes for all the (relevant and irrelevant) stimulus features. The model assumes that the relevant stimulus dimension is tagged (Kornblum & Lee, 1995, p.856). If there is stimulus-stimulus overlap, such as with coloured colour word names, identifying the correct dimension to tag will only matter when the overlap is incongruent. Hence the interference effects of incongruent (Stroop like) overlapping stimulus dimensions. As far as the Simon effect is concerned, the effect of an irrelevant spatial stimulus property resides in the automatic activation of the corresponding response code. This process is faster than the identification of the correct response code from the relevant stimulus dimension and means that a response code will already exist at the time that the correct response code is formed.

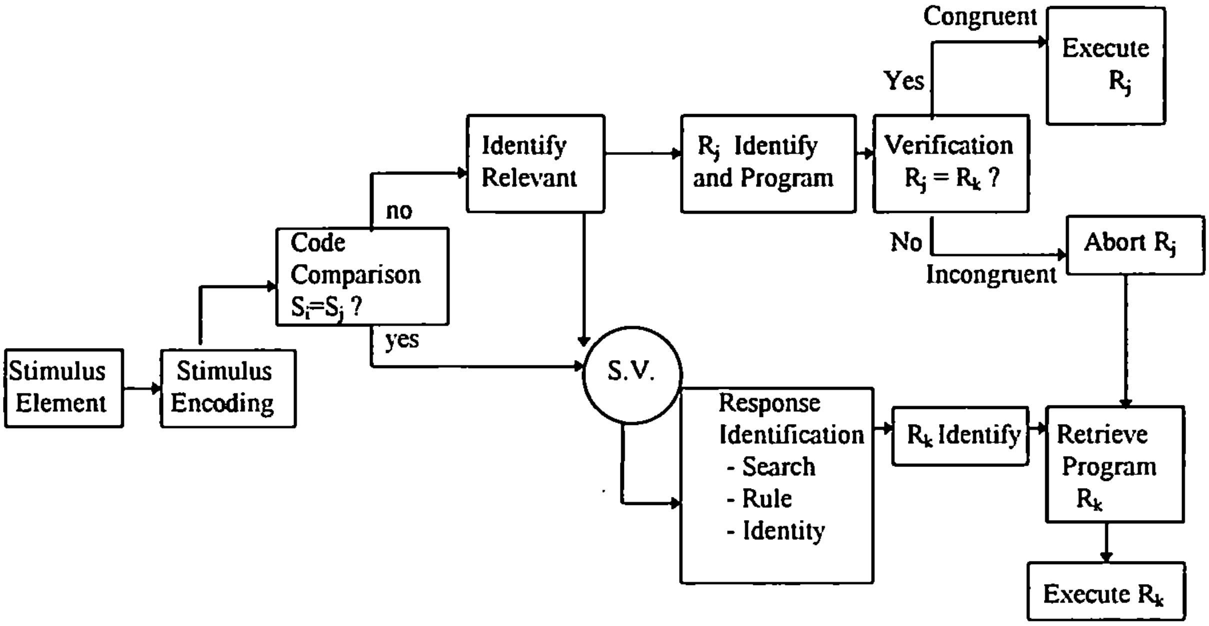

Figure 3.2. Dimensional Overlap Model of SRC (Form Kornblum & Lee, 1995). SV. stands for the stimulus vector, S_i a stimulus property that overlaps with another stimulus property and S_j one that over laps with a response property. R_j is an automatically activated response and R_k the correct response.

If the correct response code has the same value as the automatically activated response, the latter can be executed without delay. If it differs, however, the automatic reponse must be aborted and the correct response program generated and executed. Facilitation thus operates in virtue of the automatically activated response being pre-programmed, or primed, such that a simple go signal can be generated to execute it, without a new response program having to be achieved.

Physiological evidence for automatic activation of response codes

There is a certain amount of physiological evidence that irrelevant spatial stimulus properties do, in fact, generate response codes automatically. Requin & Riehle (1995) recorded neuronal activity in the motor cortex of responding monkeys during a Go/No-Go task and a simple SRC task. In the Go/No-Go task the monkeys were trained to align a pointer to a target light by the rotation of a handle which involved either flexion or extension of the wrist. Whether to make the response (Go trials) or withhold it (No-Go trials) was determined by the distance of the light. They used single neuron recording techniques to analyse the relation between response signals in Go and No-Go conditions and the activation of wrist related motor neurons in the primary motor cortex. Despite only recording cells in the primary motor cortex, the cells could be divided into three groups according to their correlation with stimulus or movement onset. Thus one group of cells' activation correlated with the onset of the visual stimulus (sensory neurons) and another with the onset of the movement itself in Go trials (motor neurons). A third group had activations that correlated with both stimulus and movement onset (sensorimotor neurons). This gradation reflects the fact, described in the first chapter, that the primary motor cortex contains populations of cells with both visual and motor properties[3]. The activation patterns for Go and No-Go trials differed only in the motor neurons and the motor component of the sensorimotor neurons, with these being activated only in Go trials. There was, however, a slight activation of motor neurons in the No-Go trials.

A further experiment employed a standard SRC task in which monkeys had to align the pointer to a left-right coloured light in the compatible condition and in the opposite direction in the incompatible condition. Whether to make a compatible or incompatible movement was determined by the light's colour. A small proportion of the neurons studied exhibited activation patterns consistent with the automatic activation of the congruent response during incompatible trials. Thus before the correct response was executed on incompatible trials some neurons showed activation patterns identical to those shown to the same stimulus when the required response was a congruent alignment of the pointer to the light location. Their data thus lends some support to the notion of the automatic activation of spatially congruent responses during spatial SRC tasks.

A study of lateralised readiness potentials (LRPs) in human subjects during SRC tasks was carried out by Eimer (1995). He conducted a series of priming experiments in which a cue could indicate the side of the forthcoming response with variable certainty. Regardless of cue informativeness it resulted in the activation of an LRP associated with a congruent response (i.e. one that corresponded to the left-right information in the cue).

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[3] As Requin & Riehle (1995) note this point is important for studies of response activation that use event related potentials such as lateralised readiness potentials (LRPs), originating in the motor cortical region, as an indicator of response preparation. Not all of the motor cortical activity making up LRPs is likely to correspond to motor preparation itself, it may well also arise from the activation of motor cortical cells with primarily visual response properties. This is only critical to interpretations of response preparation if one adopts the separatist view of visual and motor processing. From the position outlined at the end of the last chapter the activation of motor cortical cells with primarily visual properties does constitute response preparation (or a component of it) as visual and motor processes are so highly inter-related.

Thus congruent response patterns were activated even when the forthcoming target would most probably indicate a response on the contra-lateral side. This activation occurred about 200 msec after cue onset and was followed by a later activation phase at 600-700 msec after cue onset that depended on task instructions. Another important result that provides further support for the DO model of SRC was the fact that in these experiments there had to be dimensional overlap between the cue and the responses. For the experiments where responses congruent with the pre-cue were activated, the pre-cue consisted of left or right pointing arrows. When these were replaced by coloured squares no such automatic activation was observed, even though the colour of the square could provide reliable information about the side of the forthcoming response. The spatial nature of the cue and the responses thus are confirmed to be critical to the Simon effect. Eimer (1995) also attempted to rule out the possibility that the LRPs were the product of overt or covert attentional orienting. Eye movements were monitored very strictly and so overt attentional orienting could not be responsible for the results. To check for covert orienting LRPs were monitored over the occipital and parietal areas. Eimer found in all cases the LRPs arising from the motor areas to be by far the largest. The assumed lack of any effect of attentional orienting is in fact at odds with a number of studies indicating the role of attention in the Simon effect discussed below. A further difficulty with the use of *lateralised* potentials is the fact that they require the responses to be executed by the left or right hands even though it is well established that the Simon effect occurs when spatial stimulus-response correspondence takes place independently of stimulus-effector correspondence. The evidence of automatic activation arising from such studies can probably be taken to reflect one, rather than all, of the possible response codes associated with the spatial stimulus property. Thus the automatic activation of a lateralised response may only constitute one type of code (in this case effector related) that can be activated automatically (see e.g. Lamberts et al. 1992 above).

An automatically generated response code is liable to decay over time. Thus the temporal relation between the coding of the (irrelevant) spatial property of the stimulus or precue and the coding of the response relevant stimulus property is likely to affect the magnitude of the Simon effect. Hommel (1993, 1994a, 1994b, 1995) conducted a series of studies that examined this temporal relation. The results consistently implied that the Simon effect was produced by an automatically activated response code that formed, and decayed, relatively fast. The magnitude of the effect was strongly related to the time course of the coding of the irrelevant spatial stimulus property. Hommel (1993) used a variety of methods that affected the time course of the formation of the *relevant* stimulus code. These included stimulus eccentricity, signal quality, and stimulus-background contrast. Increasing stimulus eccentricity, or decreasing signal quality or contrast, all increase the time taken to identify the stimulus along the relevant dimension (square or cross, or "I" or "T" in these experiments). The time taken to register the stimuli's location, however, is relatively unaffected by such manipulations. On the assumption that the code for the irrelevant location of the stimulus is short lived (either through decay or inhibition) then the Simon effect should be greatest when the irrelevant location code is still active when its identity is coded. This is exactly what Hommel (1993) found. Manipulations that increased the time necessary to identify the stimulus along the response relevant dimension also resulted in a decrease in the Simon effect. Hommel (1994a) also produced the same results with the time taken to identify the relevant stimulus attribute manipulated by varying stimulus complexity. As a more direct check on the importance of temporal overlap between the irrelevant and relevant codes in the Simon effect Hommel (1994b) also included an experiment in which the formation of the relevant code was manipulated directly. In this case the stimulus could be built up over time so that its identity was either immediately available or only available after 196 msec. The Simon effect was approximately twice the size when the stimulus identity was available immediately, rather than after a delay. Because information about stimulus location invariably is available earlier than that about stimulus identity (i.e. to identify the stimulus its location must necessarily first be coded) it is difficult to push the temporal overlap to extremes. However, by modifying the design of such experiments to include separate response relevant and Go /No Go stimuli it is possible to give information about the required response well in advance of the irrelevant spatial information. Thus Hommel (1995, Experiment 1) gave subjects complete information about a left right response followed by a colour coded Go/No-Go signal. The latter was presented either to the right or left of fixation. Even in this case, when subjects had complete advance knowledge of what response, if any, was to be executed, the location property of the Go/No-Go signal still exerted a strong Simon effect.

A detailed investigation of the time course of the Simon effect was carried by De Jong, Liang & Lauber (1994) using distributional analyses. They proposed a dual process account of spatial SRC effects. The first process, which they term unconditional automaticity, consists of the automatic activation of the response congruent with the irrelevant spatial stimulus attribute and as such corresponds to the automatic response generation described above. The second process is akin to one proposed by Lu and Proctor (1994) and is dependent on the particular mapping rule in operation, hence the term 'conditional automaticity'. The latter process requires that a compatible or incompatible mapping rule can be given between the relevant, but non-spatial, stimulus and response dimensions. This condition is met, for example, in the standard task where a colour to colour S-R mapping is given. In this case a congruent mapping would have stimuli cueing responses of the same colour (e.g. red stimulus = red response and green stimulus = green response) whereas incongruent mappings would have stimuli cueing the non-matching response . Lu & Proctor (1994) proposed that the mapping rule that must be applied to the relevant stimulus feature to determine the correct response also is applied to the irrelevant stimulus feature. Thus if the mapping rule is congruent it will result in the activation not only of the congruent response defined by the relevant S-R dimension but also in the activation of the spatially congruent response. In contrast, with the incongruent, or reversal mapping, the incongruent spatial response will also be activated because this 'reversal rule' automatically gets applied to the spatial stimulus property. As De Jong et al. (1994) point out the two processes will have different time courses with the first time locked to stimulus presentation, whereas the second will be time locked to the response. By dividing subjects' reaction time distributions into quintile or centile bins they found the effect of this unconditional process to decline linearly by approximately 11 msec for every 100 msec increase in RT. Irrelevant spatial S-R correspondence was greatest for the fastest responses and in fact reversed for the slowest responses. This confirms other reports of the transient nature of automatically generated response codes (e.g. Hommel 1994a above) and further suggests that with long reaction times the Simon effect may actually be obscured by a reversal that takes place given sufficient time. De Jong et al. (1994) presume that this reversal at long reaction times is the result of inhibition of return or a similar process operating in the perceptual motor system. The conditional processes, in contrast, showed no differential effect of relative reaction time, supporting the notion that this process only operates at the time of S-R translation - a stage that De Jong, Wierda, Mulder & Mulder (1989) found to be tightly time locked to the overt response. There would thus now appear to be overwhelming evidence that the spatial compatibility effects, and in particular the Simon effect of an irrelevant spatial stimulus response dimension, arises from *automatic* processes, and that these are independent of task related requirements, although the latter may nonetheless affect the time course of responses in a manner that obscures the former. This point means that any manipulations that seek to determine the presence or absence of automatic response generation must take account of the effects on overall RT that they may result in.

Converging evidence supports the view that the Simon effect results from an automatic activation of a response that corresponds with a spatial property of the stimulus. What is not clear from these studies is the basis for the effect. It is unclear as to why the irrelevant spatial stimulus properties are coded at all. A possible candidate is that directional codes are formed by attentional processes. Attending to a stimulus implies that its spatial position is coded, so that a saccade can be made to it if required, and attentional accounts of spatial compatibility assume that it is this that mediates the Simon effect. Nicoletti & Umiltà (1989) tested the possibility that the current focus of attention provides a basis for allocating left-right codes to stimulus positions that result in Simon effects. Because of the many axes which can be used to partition space into left and right regions (the body midline, the head midline, the retinal meridian) they instructed subjects to maintain eye fixation on a fixation cross whilst covertly attending to a region of space cued by a filled square which remained for 500 msec (experiments 3-5). 500 msec after the covert attentional cue was extinguished a square or rectangular stimulus was presented in one of two flanking rectangular boxes and subjects had to depress either a left or right key depending on its shape. Importantly the position of the filled square cue varied randomly from trial to trial but was positioned so as to always be between two of the six rectangles that were always present. Nicoletti & Umiltà (1989) found Simon effects of the irrelevant stimulus position when that position was coded as left or right with reference to the position of covert attentional focus. Even when the six possible stimulus positions were divided into two left-right groups by a salient gap between the three left and three rightmost rectangles, its position only produced compatibility effects when analysed with reference to its left-right position from the centre of covert attention and not with reference to the left or right display groupings. Furthermore the possibility of the effect arising from eye movements was ruled out by their final experiment in which these were monitored on video.

In a more recent set of experiments Nicoletti and Umiltà (1994) tested whether manipulations that prevented subjects from moving attention to the stimuli would result in the absence of Simon effects, as their account predicts. To achieve this they used a similar procedure to their 1989 experiments except that subjects had to fixate a centrally placed cross below which one of four letters was displayed for 100 msec simultaneously with the display of the stimulus in one of the six boxes. The letters served to distinguish between regular and catch trials. One of the letters indicated that responses should be withheld whereas the other three signalled that they should be made. Under these circumstances no compatibility effects of stimulus position were observed. Nicoletti & Umiltà (1994) argue that the spatial codes that produce Simon effects have their basis in a 'pre-motor' theory of attentional orienting. According to this account, which is similar to that given by Goldberg & Seagraves (1987, see chapter 1 section 2.7), the presentation of stimuli results in the formation of motor commands that can subsequently be used to generate a saccade. They do not, however, depend on the *actual* generation of a saccade, hence the term *pre*motor. Accordingly, Nicoletti & Umiltà (1994) argue that the reason for the absence of a Simon effect in this experiment was because subjects did not shift their covert attention to the stimulus, as they had to maintain both covert and overt fixation on the central cross and letters in order to determine whether or not the trial was a catch trial. One must wonder, however, how it was possible for subjects to distinguish the square and rectangular stimuli if they had not directed any attention to them. Furthermore, and as the authors note, reaction times in this experiment were some 160 msec longer than in previous experiments using the same display but without requiring the letter discrimination. Thus the absence of the Simon effect could be explained by resource to Hommel's (1994b) spontaneous decay hypothesis or, alternatively, by the particular strategies subjects adopt during the task. They might covertly attend to the spatial stimulus first and then return to the letter stimuli in order to confirm whether or not to respond. If the order in which they attend to both stimuli varies randomly from trial to trial, premotor commands may still be being generated but also be cancelling each other out. Whatever the precise reason for the disappearance of the Simon effect in these circumstances the premotor theory has the advantage of explaining the basis for the spatial coding of the irrelevant stimulus property in the first place. The relation between the spatial code thus formed and the response remains quite abstract however. The basis for the compatibility effect is still seen as a congruence between the left-right premotor saccade command and the left-right response position rather than any correspondence between a potential response and the actual required response. Thus the account does not imply that the premotor saccade might itself potentiate a response within that side of space and therefore put the correspondence at the level of actual response potentiation. Nevertheless the fact that the focus of attention is implicated in the Simon effect undermines the view that it arises from purely relative spatial stimulus properties unconnected to the organisation of the visuo-motor system. If attention has time to realign at the position of the imperative stimulus no Simon effect is observed and yet the relative spatial properties of the display remain the same (Stoffer & Yakin, 1994). Moreover this occurs even under conditions that do not allow for the decay of the relative spatial codes of the stimuli. As Stoffer & Yakin (1994) point out, relative spatial coding and attentional focus are not merely correlated but functionally linked. The current position of attention serves as the reference point about which positional codes are formed. Stoffer & Yakin (1994) explicitly acknowledge the role of the action system in the Simon effect. The way relative codes are formed, they argue, is a direct result of the way visual attention is geared to action control. Their position is in many ways similar to that of Stein[4] (1992, see Chp. 2 sect 2.4.1) in as

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[4] Stoffer & Yakin (1994) refer to the notion of a common spatial map for attentional selection and action control whereas Stein (1992) argues against the existence of any common spatial map. However the two views are not dissimilar as the parietal system of visuomotor transformations proposed by Stein serves the same purpose as a common spatial map only more directly - in both views attention plays a direct role in coding the position of objects.

much as one of the major functions of attention is to mediate visuo-motor transformations (including, e.g., saccade commands) without resource to an explicit map of external space.

The premotor account differs from other attentional explanations such as that put forward by Verfaellie, Bowers & Heilman (1988) in which they attribute the effects to the specific readiness to respond with a particular effector. In their study subjects were given relatively reliable (80% correct) prior information about the task under four conditions. These corresponded to information about 1) the side of space in which the stimulus would appear; 2) which hand they would have to respond with; 3) both 1 and 2 and 4) neither information. The brightness of the imperative stimulus determined which hand they had to respond with. Surprisingly they found that only in the condition in which subjects were given information about which hand they were likely to use, but no information about which side of space the stimulus would appear, was a Simon effect observed. This is odd because, as Verfaellie et al. (1988) note, the original Simon effect was observed in conditions with no precues. They explain the absence of an effect here by reference to the fact that trials with precues and those without them were randomly intermixed, resulting in no 'intentional set' in the trials without precues. The gist of their conclusion is that it is the implicit or explicit readiness to respond within a particular hemispace that is responsible for the Simon effect. Under normal conditions (without any warning cues) the processing of the spatial stimulus results in a selective readiness to respond in that side of space, as responses and stimulus processing are governed by the same hemisphere. In their study this selective readiness was created *explicitly* with the intentional warning cue. Unfortunately this account does not stand up well to subsequent research. First, same hemisphere advantages are only of the order of a few milliseconds whereas the typical Simon effect is of the order of 15 to 40 milliseconds. Second, and more importantly, the studies previously mentioned have shown that relative and not absolute spatial stimulus and response positions are the principal determinants of spatial compatibility effects. Attentional factors are undoubtedly important in spatial compatibility but they are so not simply because of hemispace-hemisphere congruence effects. Furthermore the notion put forward by Verfaellie et al. (1988) of an explicit or implicit readiness to respond may well underlie the compatibility effects they obtained - but not necessarily in virtue of the hemispace/hemisphere correspondence. A readiness to respond to a particular location would suffice.

Attentional accounts of the coding underlying the Simon effect can only apply to the original Simon paradigm in which the effect occurs from the spatial congruence of the stimuli and responses. Simon effects that arise from the congruence of S-R dimensions other than those directly affecting the focus of attention cannot be attributed to attentional codes. Therefore a single mechanism based on attention cannot be sustained for all Simon effects. This of course is only a problem if one considers SRC effects, of both relevant and irrelevant dimensions, as a unitary phenomena. The notion of SRC applies to an extremely broad spectrum of stimulus-response arrangements. Because of this it is very unlikely that compatibility relations will only emerge from a single mechanism. Stimulus-response relations exist in far too many experimental and natural settings to be explained by a few restricted mechanisms. Even the subset of those settings in which S-R compatibility relations emerge from irrelevant spatial properties of the stimulus and response sets (i.e. the Simon paradigm in all its various forms) applies to too many possible arrangements to be capable of being explained by a single process. Within experimental set ups that are highly restricted in terms of both stimuli and responses then the possibility of a single mechanism explaining the compatibility relations that emerge is naturally increased. In this case, the experimental evidence from the Simon effect points to the existence of an automatically generated response code based on the spatial properties of the stimulus. This code appears to be formed automatically because of the existence of DO between the stimulus and response sets, and to have its basis in attentional processes - possibly premotor saccade commands. However, this evidence does not provide good grounds for extending this explanation to the wide variety of possible S-R relations, especially those in which the stimuli and responses are richer both with regard to their information content and relevance to the organism.

3.3. Affordances and SRC

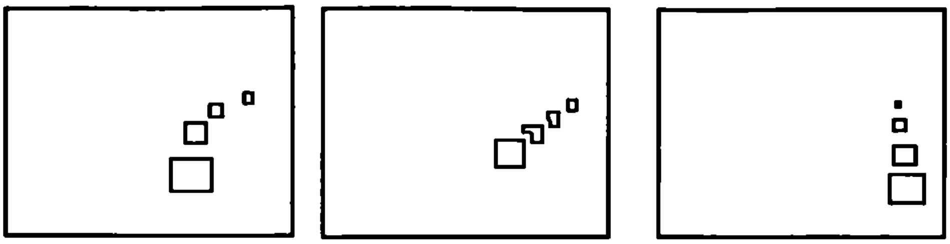
3.3.1. The role of affordances in compatibility effects.

As is apparent from the studies discussed above SRC has most often been concerned with compatibility relations between quite abstract stimuli and responses. The preponderance of cognitive coding accounts of the effects in many ways reflects the nature of the tasks used to study them. Stimuli such as coloured points and abstract shapes bear no meaningful relation (in an ecological sense) to the responses. It is not surprising therefore, that compatibility relations that emerge from these arrangements appear to be based on the way these abstract dimensions are coded. In such stimulus-response arrangements the only actions afforded by the stimuli are attentional movements. Nonetheless the motor system has been shown to play a central role in the production of spatial codes, even in these restricted environments (Nicoletti & Umiltà, 1989, 1994). Certain attentional processes are, of course, automatic by nature - one of the functions of attention, after all, being to alert the perceiver to new events.

In S-R environments that have more relevance to the visuomotor system S-R compatibilities based on the actions afforded by the environment may come into play. This approach was taken by Michaels (1988) in a study that used an SRC paradigm with moving stimuli. Here subjects sat facing a screen which contained two squares on the left and right of fixation. They operated two joy sticks with their left and right hands, aligned with the position of the squares, and responses consisted in a push on the joystick (intended to mimic a catching action). At the beginning of a trial one of the squares would appear to move toward either the ipsilateral or contralateral hand. Apparent motion was achieved by a succession of appropriately calibrated increases in size of the square and shifts in position. Subjects had to make a push response based either on the square that started to move or on the destination of the moving square, and they had to do this with either compatible (e.g. left square (or left destination)= left response) or incompatible conditions. The most interesting result was the fact that even when destination was irrelevant, and subjects based their responses on the square which moved, a Simon effect of destination occurred. Responses were faster when the square moved toward the hand that was required to make the response. Another important effect was the fact that when subjects base their responses on the destination of the moving square (in the condition in which this was the relevant stimulus dimension) the (initial) location of the moving square exerted a negative Simon effect. Responses to destination were actually faster when the *contralateral* square moved toward the hand rather than the *ipsilateral* square (see Figure 3.3). Michaels (1988) argued that the detection of an affordance (in this case catchability by a particular hand) underlay the effect. It is also, however, consistent with an interpretation based on relative motion as this was always confounded with destination. A second experiment aimed to disentangle the relative motion interpretation from the destination one. If an affordance such as catchability contributed to the effect it should be greatest when the location of the hands making the responses coincided with the destination of the moving square, whereas if the effect was principally attributable to relative coding the *absolute* position of the hands should make little difference, as long as they maintained their relative left-right positions. In this experiment Michaels (1988) repeated the first experiment but with the left and right hands operating joysticks that were centrally placed or either to the left or right of the central position. The results support the affordance interpretation. The Simon effect of destination was greatest when the hands were centrally located and thus maintained their absolute correspondence with the destination of the moving squares. In addition destination produced larger compatibility effects than location when these were the relevant stimulus dimensions.

Even though the 'catchability' interpretation is consistent with the results it still remains a speculative interpretation. An extensive examination of the affordance account of Michaels (1988) by Proctor, Van Zandt, Lu & Weeks (1993) came out against that interpretation. Proctor et al. investigated both whether the responses had to mimic the affordance of catching for the effect to occur, as well as whether or not the relative motion of the stimuli needed to afford that action. Their results were, at first sight, quite conclusive. First of all the effect occurred when subjects made simple key press responses rather than joystick push responses ruling out the requirement of an 'affordance mimicking' response. Second similar effects were obtained with stimuli that moved *away* from the hands or showed only lateral apparent motion. They also found compatibility effects of pointing arrows that cannot easily be said to afford specific actions. Proctor et al.'s results provide fairly strong evidence that what matters for spatial compatibility effects, including those of an irrelevant stimulus dimension, is the relative left-right information available in the display and not the presence or absence of affordances for action. There is, however, nothing in their results that disproves the affordance interpretation of compatibility effects, either in the Michaels (1988) experiment, or in other possible experiments involving more meaningful stimulus-response relations. Showing that compatibility effects of an irrelevant spatial stimulus dimension do not depend on that stimulus affording an action was already known from previous studies. To show that what matters for compatibility effects in an array involving moving squares is relative left-right motion, rather than affordances, one requires much more than merely showing that affordances are not necessary for similar effects to occur. The notion that affordances might enter into compatibility effects is not the same as saying that they are responsible for all such effects. That a Simon effect occurs for both ecologically redundant stimuli such as left-right coloured lights and for more meaningful richer optical displays such as used by Michaels (1988) says very little about the processes operating in the two situations. To conclude that relative coding is what matters because both arrangements contain relative codes but only one 'affordances' assumes, without supporting evidence, that the same processes are operating in both settings. More specifically it assumes that the same kind of information is being used.

Any ecologically meaningful display will be capable of being decomposed into a very large number of 'abstract' codes. As Michaels & Stins (1997) note the properties of an expanding square are numerous - at any point it has a total area, a rate of change in area etc., but the important question is what property has relevance to the organism looking at it (Michaels & Stins, 1997, p.339). The important question from the ecological perspective is what information is being detected (directly) and exercising control over behaviour at any particular time. The debate between the notion of affordances and codes is illustrated by Michaels (1993) reply to Proctor et al. (1993). Here an SRC paradigm was used that involved moving squares that moved in the first half of a semi-circular orbit or in a linear trajectory. The important change in this experiment was that for the squares involving a curvilinear trajectory their relative left-right motion was not confounded with their left-right destination. Because they were viewed only in the first half of their trajectory their relative left-right motion was always opposite to their actual destination (see Figure 3.3). Despite this, Michaels (1993) still found destination compatibility effects of comparable magnitude for the curvilinear trajectories. Unfortunately, this was only tested for the condition in which the destination of the moving square was the relevant stimulus dimension for response choice.



Curvilinear **Linear Contralateral** **Linear Ipsilateral**

Figure 3.3. Examples of the stimuli used by Michaels (1993)

Whether or not a true Simon effect would have emerged from such a display remains open. Proctor et al. (1994), however, argued that these results could still be explainable by the coding of *relative* left-right motion. Thus they suggest that relative to the linear contralateral condition, the stimuli in the curvilinear condition exhibited a rightward motion. The controversy of the interpretations reflects the inevitable confounding of cognitive codes and affordances for action mentioned above. The only occasions on which it would be possible to separate out the two accounts is when a stimulus property that affords a specific action cannot be said to be 'codable' along the same response dimension. Such occasions inevitably will be extremely rare. Any stimulus property that affects the actions which can be directed toward it invariably reflects a physical property that, conceivably, could also be coded in an abstract manner. Whether or not the Proctor et al. interpretation is correct in this case it highlights a serious problem with the coding approach. As an explanatory device it is far too universal. To take an extreme example a projectile moving very fast towards the physical location of either hand affords withdrawing the hand (fast). No doubt one could arrange things so that one was not quite dealing with purely reflexive actions. Assume the actual destination of the projectile was nominally irrelevant to the choice of which hand to make a withdrawing response (this being defined, say, by colour). Under such conditions it would be hard to argue that a Simon effect of the irrelevant destination of the projectile was a result of abstract coding of left-right relative motion! The example might be trivial but the point is not. Such an arrangement still lends itself to the abstract left-right coding of stimulus motion but one would not wish to say that absolute relations between the effectors and the actions afforded by the stimulus did not play a role in the compatibility effect observed[5]. This problem is most acute when the 'ecological' approach is pitted against the 'information processing' approach. Although there is a serious debate here regarding the way visual information is used it is not one that needs to enter into the discussion of the 'affordances for action' versus the 'abstract coding' interpretations of compatibility effects. The importance of the relation between perception and action is not dependent on the psychological tradition from which it is approached.

3.3.2. Action potentiation and affordances

The term 'affordance' has its roots in the ecological tradition where it is used to refer to the possibilities for action inherent in an environment. Affordances only take on meaning with reference to the perceiving organism's physical characteristics or its 'effectivities' (Turvey & Shaw 1979[6]). Neither of these ecological concepts necessitates a stance on the direct perception debate. Perhaps the main point of departure between the ecological and information processing approaches to perception and action resides in the former's concern with the critical information present in a visual scene rather than the representation of that scene. More specifically the ecological approach searches for so called invariant information that specifies action relevant properties. Such information, it is proposed, can be used 'directly' as it specifies, quite precisely, afforded actions, and their time courses, without resource to complex processing. One of the most widely studied invariants that has

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[5] This point is illustrated by an actual experiment. Chon & Michaels (1991) showed that withdrawal responses to terminate an electric shock to the withdrawing hand were faster than key press responses, whereas key press responses to terminate a shock to the other hand were faster than withdrawal responses.

[6] Cited in Warren (1984)

been shown to provide near complete information about actions that depend on the time to contact of an approaching object is *tau* or the inverse of the relative rate of expansion of a two dimensional surface (Lee, 1976). *Tau* has been shown to be used in a wide range of settings from the time to begin wing closure in diving gannets (Lee & Reddish, 1981) to numerous studies involving human subjects catching or intercepting moving objects (e.g. Bootsma, 1989; Peper, Bootsma, Mestre & Bakker, 1994, Savelsbergh, Whiting & Bootsma, 1991). The direct perception debate will not be entered into here (see Ullman 1980 for a detailed criticism of the notion). It is sufficient here to reiterate Marr's (1982) point that for most visual tasks the extraction of invariants presents a huge computational problem. Nonetheless the notion of affordances is extremely important. Whether detected directly or not, the purpose of vision is to guide actions and these can only be guided if action relevant information is extracted from the environment.

Action potentiation

As argued in chapter two, the visual and motor systems of humans and primates are tightly integrated. The primary purpose of vision is after all to guide actions and the development of the visual system cannot be understood without reference to the development of the motor system. The evolution of the hand, for instance, is intimately bound with the evolution of visual capacities associated with guiding actions in the near space and within the lower visual field (see Previc 1990). Because of the close link between the two systems it is plausible that the way the visual world is represented includes motor information. This notion is essentially a representational account of affordances and effectivities. It shares the ecological perspective on the importance between the physical systems of the organism and the environment, but differs in that it assumes that action relevant information is represented, rather than perceived directly. The ecological notion that affordances for action are geared to the physical dimensions of the perceiver is a natural consequence of the way visual information is represented. The action potentiation account I propose to examine in the forthcoming experiments argues that a property such as, say, object size, is represented partially in motor terms. Visual information about object size is not fully separated from visuo-motor and motor patterns associated with the hands. Viewing a graspable object results in the partial activation of the motor patterns required to perform the act the object affords. It is in virtue of this property that the representation of the object's affordances are naturally scaled to the physical apparatus of the viewer - for they are partially represented by the very visuo-motor systems *of* the viewer. The representation of object size might therefore include components such as the aperture required to successfully grasp them, the arrangement of the fingers (or grip type) and the angle the wrist needs to rotate to bring the hand into a suitable position for grasping. This notion is only a conjecture and the degree to which (if at all) action patterns are generated remains an empirical question. It makes sense, for example, to represent the orientation of the opposition space embedded in an object in a hand centred frame of reference. It is only a small step to postulate that the most efficient way to achieve this is to involve the visuo-motor system in this representation. The automaticity of the process is also a natural consequence of the way action relevant information is represented. Because the motor system is directly involved in the representation of action relevant object properties (the kind of properties processed in the dorsal visual pathway) they are activated regardless of any intention to produce an act.

The idea that merely viewing an object results in the partial activation of motor patterns that reflect its affordances naturally lends itself to the SRC paradigm, particularly the Simon paradigm. This approach assumes that a partially activated motor pattern will facilitate a response that shares components of the action the motor pattern corresponds to. To show that the actions an object affords are activated merely by viewing the object the action relevant stimulus property must be irrelevant to response determination. The responses themselves must be cued by a stimulus property other than that responsible for the generation of affordances for action. Furthermore they must consist of components of the action afforded by the irrelevant stimulus property. This set up is similar to the approach taken by Michaels (1988, 1993) but some important differences remain. First of all Michaels (1988) varied the relation between the affordance generating stimulus property (apparent motion) and the response relevant stimulus property. A truer test of whether or not an action relevant stimulus property automatically results in facilitation or interference effects requires that this stimulus property is *never* used as the cue for response selection. The second difference is that the responses need not mimic a complete action but only components of it. In Michaels (1988) joy stick responses were used that were intended to mimic a catching action. The apparent motion of the stimulus was designed to afford catching by a particular hand. One of the counter arguments against the affordance interpretation put forward by Proctor et al. (1993) was that the compatibility effect was obtained with simple key press responses rather than pushes on joy sticks. From the action potentiation account, however, this distinction is not critical. Actions contain many components, some of which may only unfold as part of a synergy, whilst others may be represented before the movement is initiated. The point is that hand selection is just as much a part of a catching action as the forward motion of the hand. Thus the action account does not require that the complete action be the response. It does however require that the responses consist in components of action that are activated before movement onset and this itself remains a matter for empirical investigation.

3.4. Conclusions

The stimulus-response compatibility paradigm provides a useful framework for investigating the activation of components of actions afforded by objects under conditions in which no actual actions toward the object are required. The affordance generating properties of the stimuli can be made irrelevant to the choice of response, enabling the investigation to be subsumed under the general framework of the Simon effect. Previous studies of SRC and the Simon effect have used highly artificial stimulus and response sets, one consequence of which is that the theories put forward to explain the effects observed have remained in a purely 'cognitive' realm far removed from the perception-action systems that govern more natural stimulus-response relations. With few exceptions the Simon effect is explained with reference to the automatic generation of stimulus codes that share a spatial dimension with the response sets. There is convincing evidence that within the artificial S-R domains mostly commonly used abstract coding plays an important part in the compatibility effects observed. This would not matter but for the fact that the concept of SRC itself covers a much wider range of stimulus-response arrangements than those from which the theories have arisen. Explanations of S-R compatibility effects based on the perception-action system, from studies using richer S-R environments, are too easily dismissed. Abstract coding processes may well contribute to compatibility effects obtained in such tasks. That they are the only type of codes operating is a much stronger claim and one that is considerably harder to test. Even within abstract S-R domains there is evidence that multiple codes can contribute to compatibility effects, including those of irrelevant dimensions (Lamberts et al., 1992).

Perhaps the most serious problem with accounts of SRC based on concepts such as dimensional overlap or relative saliency lies in their inability to adequately explain the basis of the codes generated by the stimuli. If responses and stimuli share a left-right spatial dimension, for example, it is asserted that the dimensional overlap between the S and R spatial dimensions results in the automatic activation of the congruent response codes. No explanation as to why or how this automatic activation takes place is forthcoming. A 'physical' compatibility relation between stimulus and response is not assumed to be responsible for the effects. Rather the emphasis is on the match between the various conceptualisations of the stimulus and response arrangements. Thus the Simon effect is explained by congruence effects between stimulus and response *codes* rather than between the stimuli and responses themselves. Whilst the action potentiation account put forward above and in the first chapter suggests that action 'codes' could be responsible for certain compatibility relations the two types of coding are very different. The action potentiation account proposes that a response code is activated by the affordances of the stimuli for certain actions. Such a response code actually consists in a multiplicity of representations within the visuo-motor system, some more sensitive to visual properties of the stimulus and some more sensitive to motor properties. None of these codes, however, arise from dimensional overlap between the S and R dimensions - they do not act like cognitive labels. In contrast, abstract coding accounts imply that stimulus dimensions act more like high level labels. An automatically activated response code will consist in motor activation, in as much as the physical response is indeed activated. However the process by which this takes place is very different. The automatic activation is assumed to arise from higher level codes based on the overlapping stimulus dimension. As such it acts just as any other rule based signal. The activated response is not the result of a continuous stream of visuo-motor activity. As mentioned before this might well amount to a reasonable description of the processes occurring in highly abstract artificial S-R environments. Even within such environments, however, studies aimed specifically at understanding the basis for the automatic coding of irrelevant stimulus dimensions do not support this view. The studies by Nicoletti & Umiltà (1989, 1994) suggest an overlapping dimension of location produces codes that are not based on similarities inherent in the stimulus and response structure but on actual motor commands generated by the affordances present (in this case for saccades). Despite claims to the contrary the action system is important even within highly artificial S-R environments. The following chapters examine the role of the action system in S-R arrangements involving more ecologically meaningful stimuli and responses.

4. Chapter 4: Object orientation and the priming of bi-manual responses.

4.1. Overview

This chapter describes two experiments investigating the role of object orientation on the priming of left-right hand responses. In the first experiment subjects had to reach out and grasp an oriented object using either their left or right hands. When the hand of response was cued after object exposure, by a high or low pitched tone, the orientation of the object produced marked compatibility effects, particularly on the dominant hand. Thus reaching responses were initiated faster when the orientation of the object facilitated the same hand of response as that cued by the tone stimulus. These results are similar to those of Klatzky et al. (1995) on object shape and grasp type. When actual reaching and grasping movements are required object orientation as well as object shape exert compatibility effects that affect movement initiation times.

The aim of the second experiment was to determine whether object orientation primed a particular hand of response even when no actual reaching movement was to be performed. Given the hypothesis outlined at the end of the last chapter it was proposed that an object, viewed in the reaching space, would potentiate some of the actions associated with the basic reach and grasp movement. In particular, when the orientations of the objects were deliberately chosen to make them maximally compatible with a reach and grasp movement of either the left or right hand it was proposed that responses congruent with this orientation would be faster than those incongruent, despite the fact that object orientation was irrelevant to response determination. The effect of object distance was also investigated as this has implications for the affordances offered by the object. Thus the objects were presented both within and beyond the reaching space. In Experiment 2 real objects were presented to subjects in orientations compatible with a left or right hand reach and grasp movement. They made left-right key press responses depending on the inversion of the object. The results failed to show a compatibility effect of object orientation in either distance condition. It is argued that the lack of effect cannot be taken as direct evidence against the action potentiation account because of the nature of the stimuli used. Specifically subjects had to direct their attention to one side of the objects in order to determine the correct response. The direction of this attention shift was always opposite the left-right graspability of the object and could therefore cancel out any effects of the latter.

4.2. Experiment 1: Object orientation and the initiation of reaching and grasping movements

4.2.1. Introduction

The orientation of many common objects intuitively would appear to affect the ease with which they can be reached for and grasped by a particular hand. In many encounters with objects the actual choice of hand used to grasp them is not determined by the object's orientation but by other, more robust considerations, such as which hand is nearest or free. However, when both the hands are free, and centrally placed, orientations that selectively favour a particular hand can be chosen for many objects. These objects need not only be those with protruding handles, such as pans and jugs, but also those whose main grasping axis lies along the main axis of the object itself- a hammer or knife for instance. At the end of the last chapter it was proposed that even viewing an object without any intentions to make an action toward it involves the potentiation of certain actions. A three level hierarchy of the actions an object affords can be made. At the first level are those affordances that critically depend on the instantaneous visual properties of the object - such as orientation and position. At the second level the affordances of an object are directly related to its intrinsic visual properties. By intrinsic is meant those visual properties that are relatively invariant over changes in viewpoint and distance i.e. those that would be represented in the sort of 3D model that Marr (1982) proposes. At the third level an object affords certain actions in virtue of its functional properties and its identity. In this sense a pen affords writing, a knife cutting and so forth. These affordances are directly tied to the objects' physical properties (a knife must be sharp to afford cutting, a pen must have a nib) but only loosely tied to their visual properties. There is no set of defining visual features for a pen or knife - there may be clues, but the critical property is whether or not it writes or cuts efficiently (paper can cut, no doubt, but can only be said to afford cutting in a very obscure sense). This breakdown is by no means absolute, there being a certain degree of overlap between all three proposed levels. However it serves a useful distinction for descriptive purposes as well as for postulating where action potentiation takes place. Following from the work of Goodale (1993) the kinds of affordances I propose to be represented automatically when an object is viewed are those that relate principally to the first level that of 'micro-affordances', although motor patterns may well be activated by the second level also. This is so because relatively invariant object properties such as perceived size also have a direct bearing on the kinds of actions (such as the grip size needed to grasp them) that they afford. There is a possibility that other, higher level, actions are also potentiated. The reason for restricting the initial hypothesis to the potentiation of actions at earlier, lower levels, is that these form the basis (or motor vocabulary) from which subsequent action plans can be generated. As such they remain relatively 'intention free' and therefore are a more likely candidate for potentiation in the absence of explicit intentions to perform a specific action. The first experiment aimed to provide confirmation that the orientation of graspable objects does actually affect the ease with which a grasping movement can be made toward them. It was predicted that reaching movements to objects oriented so as to be more compatible with a grasp by a particular hand would be initiated more quickly by the compatible hand.

4.2.2. Method

Subjects

22 subjects took part in the experiment. All subjects were students at the University of Plymouth and had normal or corrected to normal vision. They were paid £3.00 or received

course credit for participating. They were told that they would have to reach out and grasp objects and none of them reported any motor deficits.

Apparatus and materials.

The stimuli consisted of ten common objects whose orientation was predicted to affect the ease with which they could be reached for, and grasped, by a particular hand. Five of these had protruding handles and five did not. The objects were displayed under strict tachistoscopic conditions by means of a stimulus presentation box with a one way glass screen (see Figure 4.1). Objects were placed inside the box by the experimenter who read the object and its orientation from a computer screen that was placed out of sight of the subjects. Two microswitch response keys were located at the back of the box, centrally placed and 40 cm apart. Between trials the two lights inside the presentation box were switched off and a light above the glass screen was illuminated. This prevented subjects from being able to see inside the presentation box, as there was very low illumination inside the laboratory. Objects were illuminated by switching from the outside light to the two inside lights. A list of the objects used is given in Table 4.1.

Table 4.1. List of objects used in Experiment 1.

Serving spoon	Large stapler
Frying pan	Book
Hammer	Oblong box
Wooden Mallet	Tea pot
Saucepan	Plastic Jug

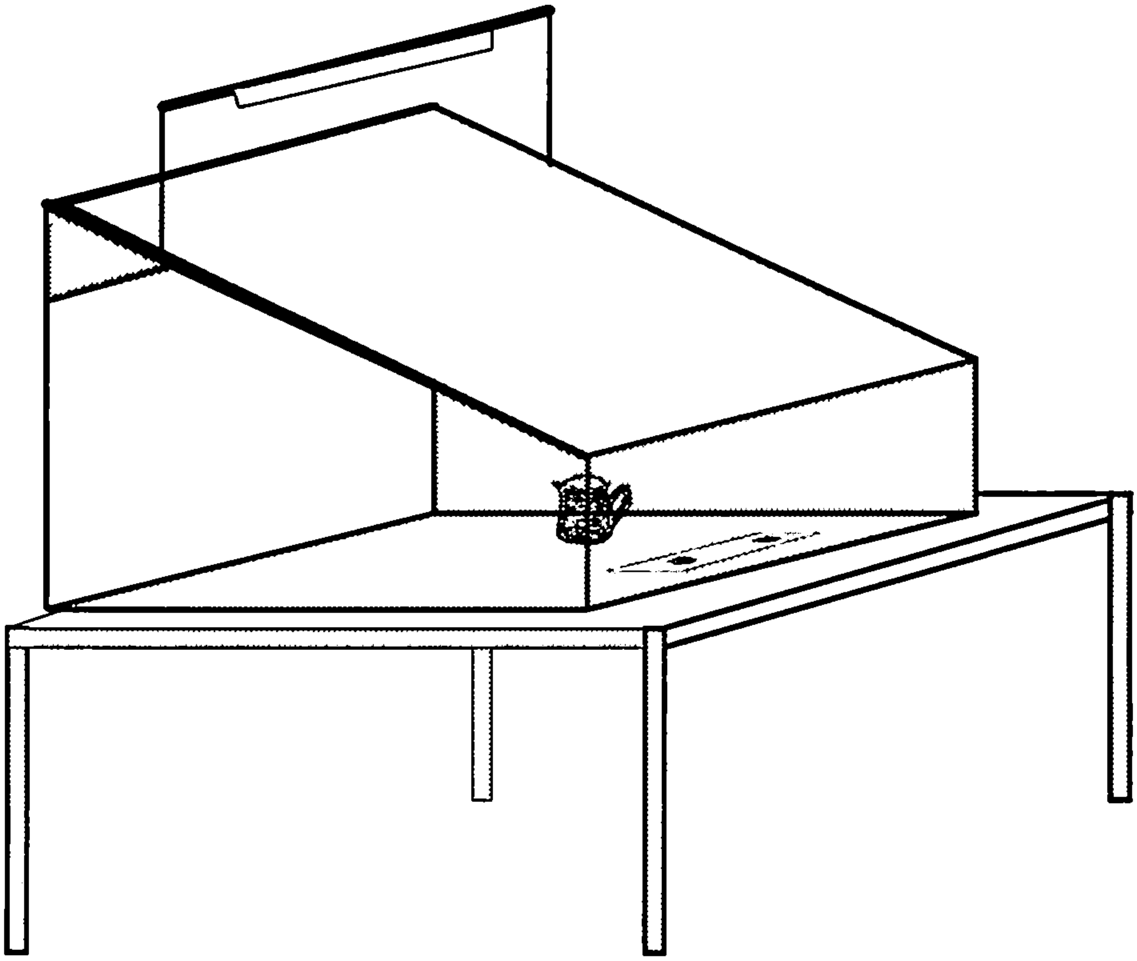

Figure 4.1. The apparatus used to display real objects under tachistoscopic conditions. Subjects were seated with their hands resting on the response keys inside the box. Objects were placed inside the box from the wider end by the experimenter.

Procedure

Each subject was randomly assigned a mapping rule of tone (high or low pitch) to hand of response (left or right). They were instructed to keep both response keys depressed at the beginning of each trial. If either key was not depressed the trial would not begin and subjects would see a flashing red light reflected on the one-way glass screen. When both keys were depressed the red light would come on and stay on for 1 second after which the light inside the box would immediately come on, illuminating the object. The objects were positioned centrally, 15 cm in front of the response keys. 200 msec after the object was illuminated a tone was given which instructed subjects to reach out and grasp the object with either their left or right hand, depending on the mapping rule assigned at the start of the experiment. Subjects were instructed to reach out and grasp the object and lift it a few millimetres off the surface. This was to ensure that their grasps were not merely pointing movements. They were told, at some length, to make their movements as fast as possible, whilst ensuring that they lifted their hand off the response key and reached toward the object in one smooth movement. This was to avoid subjects adopting a strategy whereby they simply reacted to the *tone* by releasing the key and then planned their reaching movement to the object - resulting in two separate movements. Error responses were immediately followed by a short bleep on the computer. Each object was presented 3 times in each orientation x tone condition, giving a total of 120 trials. In addition there were 24 'dummy' trials in which no object was presented. This was to minimise any tendency to respond automatically to the tone without first viewing the object. During dummy trials both response keys had to remain depressed. The order of stimulus presentation was randomised for each subject. Each subject received 20 practice trials before starting the experiment.

4.2.3. Results

Response times.

One subject was removed from the analysis because of an error rate greater than 10%. A further subject (randomly chosen) was removed to give equal numbers in each mapping. For the rest, condition means were obtained after excluding error responses and reaction times greater than two standard deviations from subjects' overall means. Dummy trials were also excluded from the analysis. An ANOVA was carried out on subjects' condition means with the factors Response (left or right), Orientation (left or right) and Mapping (right hand response-high tone/left hand response-low tone (RH_High), or the reverse (LH_High)). There were significant main effects of Mapping and Object Orientation. Response times in the RH_High mapping (M= 455.30) were on average 60 msec faster than those in the LH_High mapping (M=515.87), [$F_{(1,18)}$= 4.72, p= 0.043]. Responses to Objects oriented toward the right (M= 479.6) were on average 11 msec faster than those oriented toward the left (M=491.4), [$F_{(1,18)}$=8.91, p=0.008]. There were also significant interactions between mapping and response and that predicted between object orientation and response. Right hand responses in the RH_High mapping (M=437.95) were on average 83 msec faster than right hand responses in the LH_High mapping (M=521.52). In contrast, for left hand responses the advantage for the RH_High mapping was only 37 msec, (for the RH_High mapping M=472.64, for the LH_High mapping M=510.21), [$F_{(1,18)}$= 8.65, p= 0.009]. This interaction is displayed in Figure 4.2. The most important finding was that the interaction between object orientation and the hand used to reach for and grasp the object was as predicted. For right hand reach and grasp responses initiation times tended to be faster when the object was oriented to the right (M=463.1) rather than to the left (M=496.4) whereas for left hand responses they tended to be faster when the object was oriented to the left (M=486.4) rather than to the right (M=496.5), [$F_{(1,18)}$=5.70, p=0.028], see Figure. 4.3 and Table 4.2

Pairwise (t test) comparisons showed that for right hand responses the effect of object orientation was significant [t=2.59, $t_{(.05,18)}$=2.101] whereas for left hand responses it was not [t=.78, $t_{(.05,18)}$=2.101]. An ANOVA was also carried out including handle as a factor. The presence or absence of a handle showed no significant effects and was not analysed further.

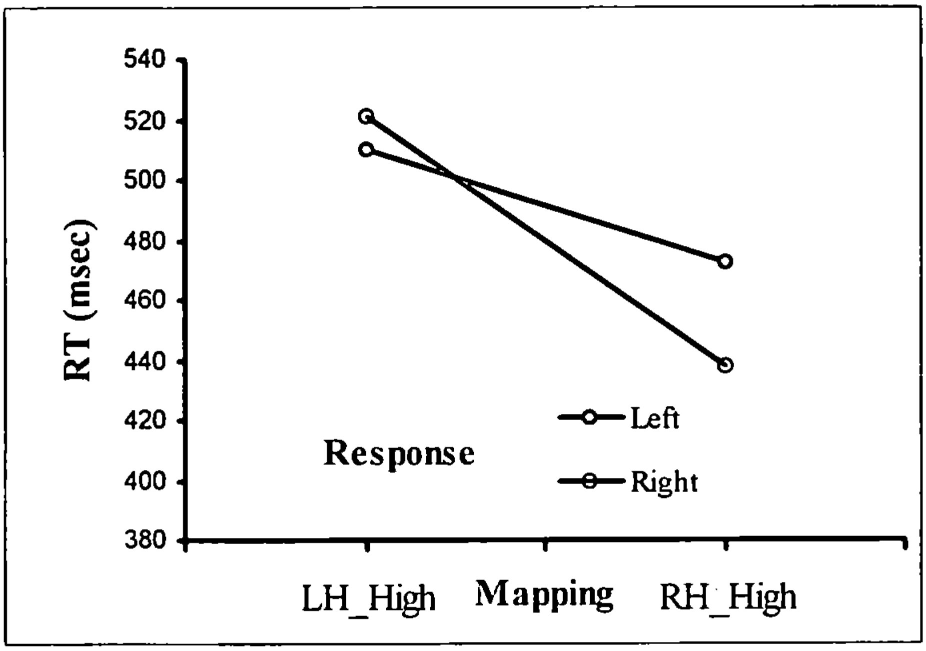

Figure 4.2 Mean correct RTs. for Experiment 1 as a function of mapping and response. Mappings RH-High = right hand for high pitched tone, left hand for low pitched tone; LH-High = reverse mapping. All RTs. in msec.

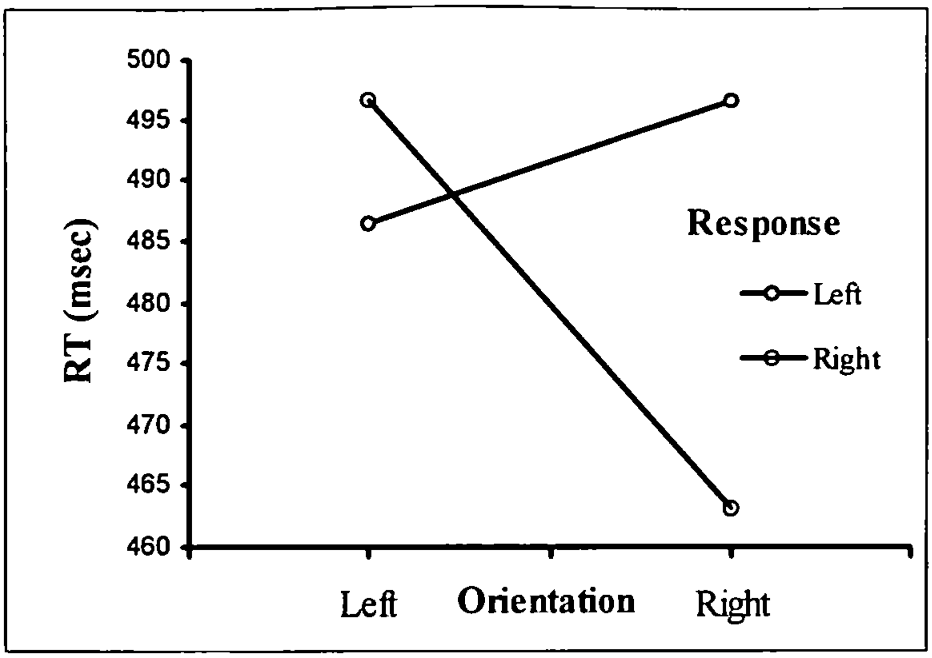

Figure 4.3. Mean response times by hand of response and object orientation for Experiment 1. All response times in msec.

Table 4.2. Mean response times (in msec), standard deviations and (% errors) for Experiment 1 by response and object orientation.

	Response	
Orientation	**Left**	**Right**
Left	**463.06** 73.6 (2.83)	**496.47** 75.76 (2.83)
Right	**496.42** 85.18 (2.0)	**486.38** 62.52 (3.33)

Error rates.

The average error rate was low (2.75%) and an ANOVA on subjects' error rates showed no significant effects.

Materials analysis.

An analysis of the data with objects rather than subjects as a random factor gave a similar pattern of results to that of the subjects analysis. There were significant effects of mapping [$F_{(1,9)}$=127.36, p<.001] and object orientation [$F_{(1,9)}$= 7.36, p= 0.024] both of which showed identical patterns to the subjects analysis. There were also significant interactions between hand of response and mapping [$F_{(1,9)}$=26.88, p<.001] and the effect of most interest, between hand of response and object orientation [$F_{(1,9)}$=19.38, p= 0.002]. As with the main effects both of these interactions had the same form as those found in the subjects analysis. In addition, however, there was a significant three way interaction between hand of response, object orientation and mapping, not observed in the subjects analysis [$F_{(1,9)}$=5.16, p=0.049]. Separate ANOVAs on each mapping condition revealed that the interaction between hand of response and object orientation was significant in both, but more pronounced in the LH_High mapping [$F_{(1,9)}$=9.52, p= 0.013 (RH_High); $F_{(1,9)}$=15.94, P=0.003 (LH_High)].

Supplementary Analyses[8]

An analysis of the subject data using both mean median response times and mean Log response times gave the same pattern of results as that using two standard deviation cut offs. For the effect of most interest (the interaction of object orientation and response) the F statistics were [$F_{(1,18)}=6.96$, $p=0.017$ (medians); $F_{(1,18)}=6.92$, $p=0.017$ (Log RT)].

4.2.4. Discussion

The results of the first experiment confirm that the orientation of a centrally placed object affects the speed with which a reach and grasp movement can be made towards it with a particular hand . This is to be expected since the awkwardness of a reach and grasp movement intuitively would seem to be affected by the orientation of the graspable axis of the object. However, this fact alone does not imply that movement *initiation* times (as opposed to movement times) would be affected. The study therefore shows that processes occurring before the start of the movement are affected. In this respect the experiment shows a similar pattern of results to that found by Klatzky et al. (1995) on movement initiation times to grasp shaped objects by either compatible or incompatible grip types.

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[8] In all the experiments reported two supplementary analyses were carried out on the response time data. These were always the same and chosen beforehand. These were done because of the difficulty associated with outlier responses. There is no *a priori* method available for determining the most efficient means of eliminating the influence of outliers, as this depends on advanced knowledge of the type of effect present. Reaction time data is not normally distributed and can be modelled with the ex-gaussian distribution. This distribution has three parameters: the mean, μ and standard deviation, σ, of the normal distribution and τ, the parameter and mean of the exponential. $\mu + \tau$ provides a good approximation to the mean of the distribution and τ to the standard deviation. Any effect of conditions can be present in one, or both, of these two parameters associated with the distribution . The best method for dealing with outliers depends on where the effect lies. For a full discussion of this problem see Ratcliffe, 1993).

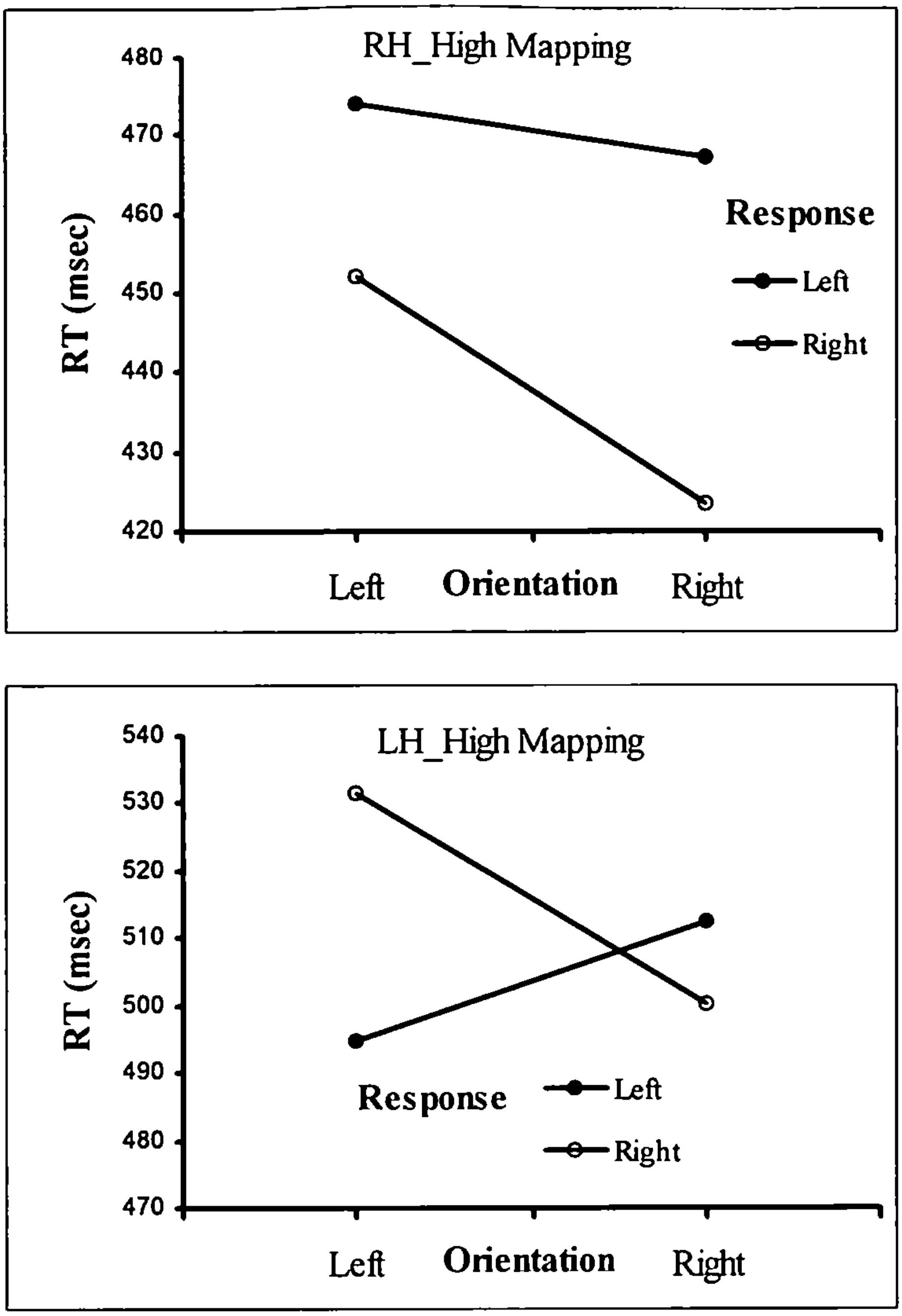

Figure 4.4. Materials analysis by mapping, hand of response and object orientation for Experiment 1.

These authors found the effects of compatible grip type/object shape conditions was almost entirely in the initiation rather than movement time. As with hand shape, the choice of hand itself, appears to be a component of the preplanning of a movement that is affected by the physical properties of the object. The study does not, of course, determine whether or not object orientation actually *primes* a particular hand of response. Two possible processes (not mutually exclusive) could be involved in the facilitation/interference effects observed. First, the orientation of the opposition axis of the object might automatically feed into a system involved in (among other components) determining the hand in the best position to make a reach and grasp movement. Such a system could correspond to one of the visuo-motor schemas proposed by Iberall & Arbib (1986). In this case facilitation effects would be based on the agreement of the hand of response cued by the tone and the hand already activated by the object's orientation. In compatible trials the movement could be executed following the tone without much delay, as the correct response would already be partially prepared. In contrast, on incompatible trials the response activated by the object would have to be aborted and that cued by the tone prepared, before the movement could be initiated. Such a process implies that the orientation of the object automatically activates a hand of response as subjects know that the only information relevant to determining the hand of response is the tone cue. The second possibility, in contrast, assumes that the facilitation/interference effects arise after the tone cue is given. In this case no hand is activated automatically by the visual properties of the object. Instead the planning of a reach and grasp movement by the cued hand takes longer when the object's orientation is incompatible than when it is compatible. The organisation of the visuomotor system would suggest, however, that action relevant visual information is fed forward to motor systems in a continuous manner rather waiting to be informed by an arbitrary signal. It is likely, therefore, that at least some of the compatibility effects observed in Experiment 1 resulted from the first process outlined above, but may also have been amplified by the second. In this experiment subjects had explicit intentions to make reach and grasp movements. Under these conditions it appears that object orientation produces compatibility effects on the hand of response - at least in the case where the object orientations and positions of the responding hands are chosen so as to maximise this possibility. It does not imply that the compatible hand of response is activated when no explicit intention to make a reach and grasp movement is present, that is when the object is simply viewed. What it does show, however, is that hand of response, in relation to object orientation, is a likely candidate for such activation. The purpose of Experiment 2 was to examine this possibility.

4.3. Experiment 2: Choice reaction time responses to oriented graspable objects.

4.3.1. Introduction

Experiment 2 had two primary aims. The first was to determine whether or not the orientation of a graspable object potentiated a hand of response even under conditions in which no explicit reach and grasp movement was called for. The second was to examine the effect of distance on any such activation. As was mentioned in the discussion of Experiment 1 object orientation could exert its effect on hand choice either only after the hand had been cued or before this stage, from the direct activation of the compatible hand by the visual properties of the object. The action potentiation account suggests that the actions an object affords will be activated simply by viewing the object. The visuo-motor patterns associated with the afforded actions are proposed to be an intrinsic part of the representation of the object rather than dependent on a specific goal. Testing this proposal requires examining the execution time of components of afforded actions under conditions in which the afforded response is not explicitly called for. Responses that share a component of an action that the object affords should be facilitated merely by viewing the object. This can be achieved, as mentioned at the end of the last chapter, by examining the effect of an action relevant stimulus property within a Simon paradigm. In this way the stimulus properties that are proposed to directly activate certain responses can be made nominally irrelevant to the actual task. At the same time the responses can be made to consist of components of the afforded actions. In this experiment the effect of object orientation on the execution time of choice left-right key press responses was examined with left-right responses cued by object inversion. Thus as far as the explicit task demands were concerned object orientation was irrelevant. The arrangement can (loosely)[9] be classified as a Type 3 SRC ensemble (Kornblum et al., 1990) in which there is dimensional overlap between the *irrelevant* stimulus property but no overlap between the relevant stimulus dimension. It is important to point out that hand dominance may override the effect of horizontal object orientation in many instances of everyday prehension. Thus we may often reach for and grasp an object with our dominant hand even though its orientation is not maximally compatible with a grasp made by that hand. The data from Experiment 1 suggest that the effect of object orientation on the compatibility of an actual reaching movement is, in fact, greatest for the dominant hand. This, however, does not affect the conclusions that can be drawn from the present study. Even though in instances of everyday prehension hand selection will rarely be exclusively determined by object orientation, given a particular hand used, the horizontal orientation nonetheless makes it more or less compatible with that hand. In this experiment the horizontal orientation of the object can be said to be more or less compatible with the cued hand (whether or not the cued hand would have been used to grasp the object in real life). The critical comparisons are between the response latencies for objects oriented to the left and right for each hand.

Experiment 2 also aimed to investigate the role of object distance on any compatibility effect observed. The activation of a reaching response might be expected to occur only, or primarily, when the object is within the reaching space. The lesion studies of Rizzolatti et al. (1985) support this possibility. If the attention systems governing regions of space are linked to the motor systems controlling actions within those spaces, as their results suggest,

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[9] Loosely because it is not actually clear whether or not object orientation and left-right responses do have dimensional overlap. Although the orientations of the objects were chosen to be maximally compatible with a left or right reach and grasp movement this 'left-right' dimension is not necessarily available perceptually. It certainly is not as obvious a structural feature of the stimulus set as left-right stimulus location. The results of a later experiment (Experiment 4) suggest that object orientation is not actually represented along a left-right dimension at the level of stimulus encoding at least.

then those actions may only be potentiated when the corresponding attention systems are operating. On the other hand the representation of a visual object might involve the activation of motor patterns even though the action cannot be performed given the current position of the object. The grip type required to grasp an object, for instance, is not dependent on where the object is. This distinction is similar to the intrinsic-extrinsic distinction put forward by Jeannerod (1994). That distinction essentially refers to separation of object properties according to whether they represent invariant properties (perceived size, weight etc.) or ones that depend on instantaneous position in space (orientation, distance, location).

4.3.2. Method

Subjects

The subjects were 30 students from the University of Plymouth. All had normal or corrected to normal vision and were right handed by self report. Subjects were paid £3.00 for their participation.

Materials

The stimuli for this experiment were twenty common household objects such as serving spoons, jugs, sieves. Most of the objects had handles and could easily be defined as upright or inverted. As in the first experiment they were chosen so that their left-right orientation affected the ease with which they could be grasped, when centrally placed, by the left or right hands of the subjects. A list of the objects used is given in Table 4.3.

Table 4.3. List of objects used in Experiment 2.

Metal Serving spoon
Plastic serving spoon
Plastic Ladle
Plastic Ladle
Metal sieve
Plastic sieve
Frying pan
Frying pan
Plastic jug
Metal spatula
Plastic spatula
Handled Colander
Large plastic jug
Coal scoop
Metal serving spool
Aluminium Sauce pan
Enamel Saucepan
Metal Ladle
Spatula
Coffee Pot

Apparatus and Procedure

Subjects were seated in front of the one-way glass box described in Experiment 1. They rested the index and middle fingers of their left and right hands on two small plastic response keys attached to separate micro-switches. The response keys were 25 cm apart. The objects were placed either within reach (15 cms from the hands) or beyond reach (100 cms from the hands). Before the start of the experiment they were told that they would have to make reaction time keypress responses using the left or right hand according to the inversion of the object. The definition of upside-down or upright was explained with examples of each object in the upright and inverted position. Objects were defined as upright or inverted according to use, so that a serving spoon with the back of the spoon facing up was deemed inverted. No subjects experienced any difficulty with this definition of inversion. A mapping rule was pseudo-randomly assigned to each subject so that there were an equal number of subjects in each mapping condition. In the RH-UP mapping subjects were told to press the right key with their right hand if the object was upright and the left key with their left hand if inverted, and vice versa for the LH-UP mapping. Subjects were instructed to react as fast as they could whilst maintaining accuracy. Incorrect responses were followed by a short tone on the computer.

The order of the distance manipulation was blocked and pseudo-randomised so that within each mapping condition there were equal numbers of subjects who received the objects within the reaching space and beyond it, in each block. Each subject received two blocks of 160 trials in which each object appeared twice in each inversion and orientation. Each trial started with a warning tone which was followed after 500 msec by the illumination of the object within the box. The object remained illuminated until a response was made or three seconds had elapsed. The second trial proceeded automatically with a delay from the response to the next warning tone of 5 seconds. Subjects were told that they could halt the progression of trials by depressing either response key. The next trial would then be postponed until the key was released.

A short 2 minute break was given after each 80 trials. After 160 trials the distance of the objects was changed and subjects were shown where the objects would now be positioned. The objects were placed in position by the experimenter who sat at the other end of the stimulus box. On each trial the object to be placed in the box and its orientation was displayed on an Acorn Archimedes computer out of sight from the subject. The object and orientation of the trial +1 object was also displayed. Two small crosses marked the position of the centre of the object at either the near or far position.

Each block contained 160 trials in which each object appeared twice in each inversion and orientation.

4.3.3. Results

Response times.

One subject was removed from the experiment as their error rate exceeded 10%. For the analysis, a further randomly chosen subject from the opposite mapping condition was removed to make for equal numbers within each mapping condition. For the rest condition means were obtained after excluding errors and reaction times more than 2 standard deviations from each subjects overall mean. These were then analysed in a partially within subjects ANOVA with the within factors Distance (within or beyond the reaching space), Object orientation (left or right), Response (left or right) and the between subjects factor Mapping (RH-UP or LH-UP). There was a significant main effect of mapping with subjects on average producing faster reaction times in the RH-UP mapping (M=522.48) than the LH-UP mapping (M=584.77), [$F_{(1,26)}$=7.23, p=.012]. The only other significant effect was the two-way interaction between response and mapping displayed in Figure 4.5. This effect, which occurs quite frequently in later experiments, is most easily understood as a main effect of object inversion as the combination of response and mapping rule determines whether or not the object was upright or inverted. In the RH-UP mapping right responses (to upright objects) (M=512.2) tended to be executed faster than left responses (to inverted objects) (M=532.8). In the LH-UP mapping, in contrast, right responses (to inverted objects) (M=586.6) tended to be executed slower than left responses (to upright objects) (M=583.0), [$F_{(1,26)}$=6.89, p=.014]. As can be seen from Figure 4.5 the effect of object inversion on reaction time appears to be greatest for the RH-UP mapping.

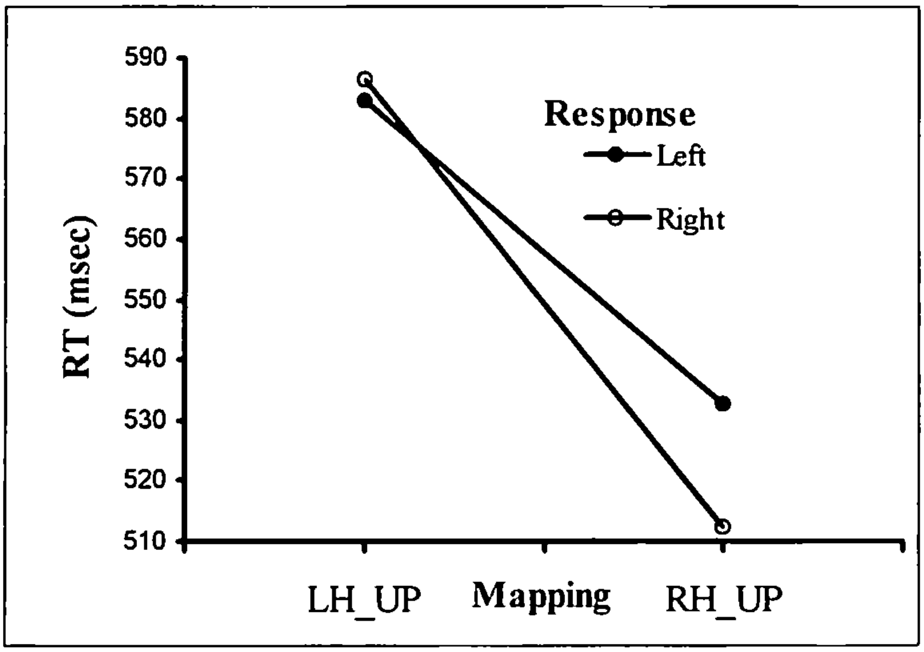

Figure 4.5. Mean reaction time for Experiment 2 as a function of Mapping and hand of response. (RH-UP = Right hand for upright objects, Left hand for inverted objects. LH-UP = reverse mapping.

The effects of main interest were the interaction between left-right response and left-right object orientation and the interaction of this effect with distance. Neither of these effects were significant. In fact the pattern of response times and error rates are the reverse of that predicted (see Figure 4.6), although neither the two-way interaction between response and orientation [$F_{(1,26)}$=1.32, p>.25] or the three-way interaction between this and distance [$F_{(1,26)}$=0.22, p>.6] approached significance.

Errors

The overall error rate for the experiment was 3.9% and an analysis of subjects' error rates showed no significant effects.

Materials Analysis

Analysis of the data with objects as a random factor showed a similar pattern to the subjects data. The main effect of mapping was highly significant [$F_{(1,19)}$=407.7, p<.0001]. In addition there was a significant effect of response with right hand responses (M=548.3) being executed faster than left hand responses (M=557.8), [$F_{(1,19)}$=10.26, p=.005]. The same pattern was evident in the subjects analysis but only approached significance [$F_{(1,26)}$=3.4, p=.076]. As in the subjects analysis the interaction between response and mapping was significant and showed the same pattern [$F_{(1,19)}$=17.26, p<.0001]. The only other significant effect, in contrast to the analysis by subjects was the interaction between response and orientation. This showed the same pattern as the subjects data (see Figure 4.7) but was significant [$F_{(1,19)}$=4.46, p=.048]. This effect did not interact with distance [$F_{(1,19)}$=.02, p=.88].

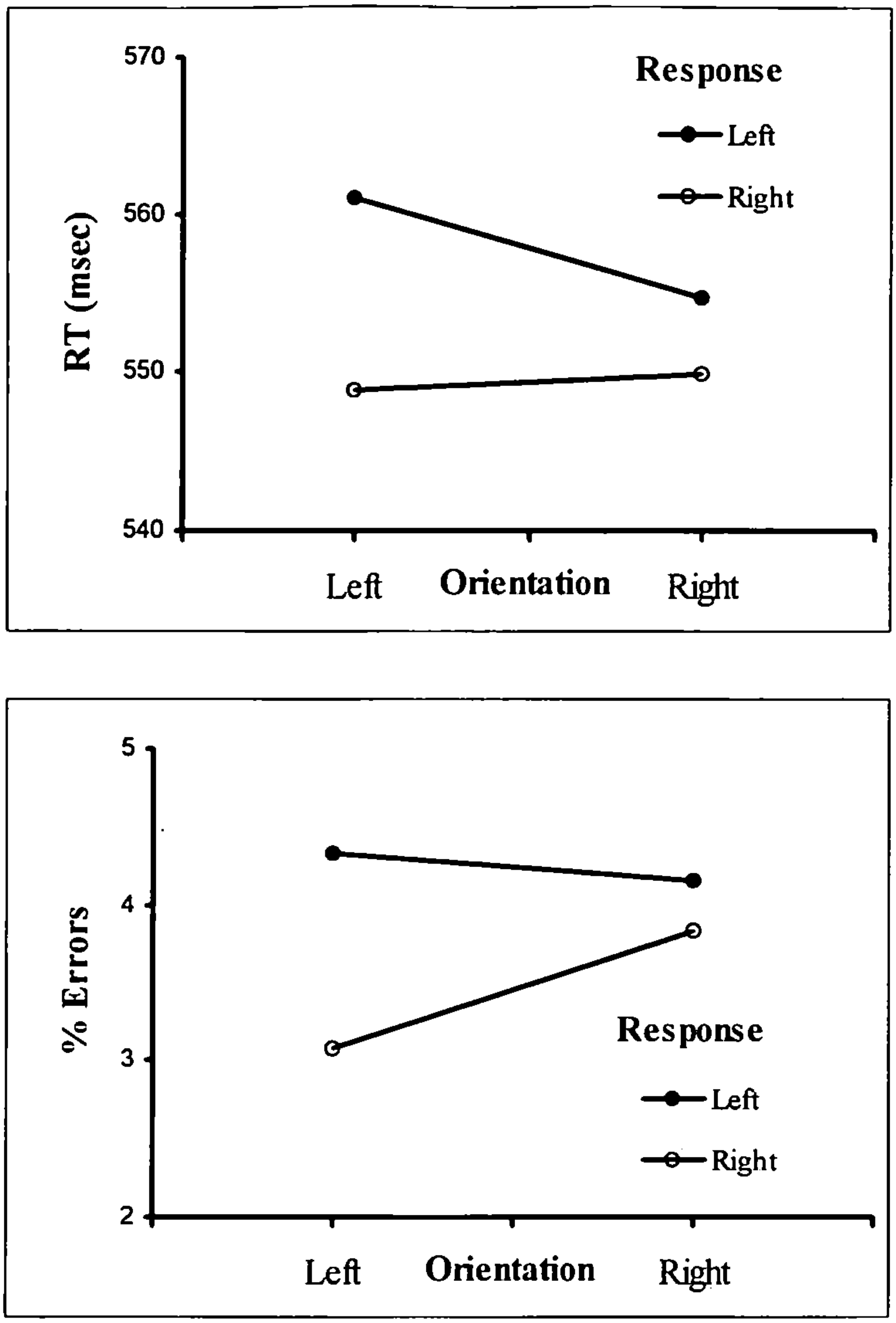

Figure 4.6. Mean reaction times and error rates for Experiment 2 as a function of response and object orientation.

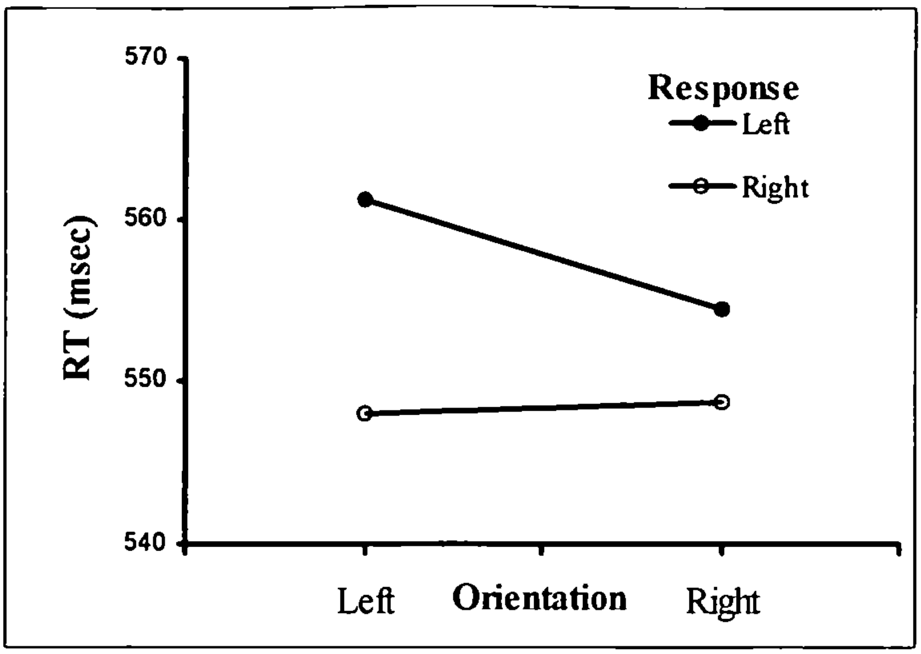

Figure 4.7. Response by object orientation interaction for the materials analysis of Experiment 2.

Supplementary analyses

The data was also analysed using median RT and Log RT to confirm the results using 2 standard deviation cut offs. These analyses showed an almost identical pattern to the initial analyses except that the main effect of response was significant in the analysis by medians [$F_{(1,26)}$=5.3, p=.029]. This effect approached significance in the original analysis [$F_{(1,26)}$=3.4, p=.076] and amounts to an overall 8.5 msec speed advantage for right hand responses.

4.3.4. Discussion

The main effect of mapping is consistent with the results of SRC studies using more abstract displays. A fairly reliable finding when using vertical stimulus positions and horizontal response positions is that mappings assigning a top stimulus to a right response produce faster RTs. than the reverse mapping (see, e.g., Weeks & Proctor, 1990). According to Weeks & Proctor (1990) this reflects the advantage of matching the relative saliency of the stimulus and response codes in the mapping rule. Thus the RH-UP mapping assigns the most salient upright stimulus with the most salient right response and the least salient inverted stimulus with the least salient left response. As mentioned above the interaction between response and mapping rule can be most parsimoniously explained by the fact that the combination of these two factors determines whether or not the object was upright or inverted on any given trial, and responses to upright objects tend to be faster overall than to inverted ones. The most important result of the experiment was the lack of the predicted interaction between response and object orientation or of the interaction between this effect and object distance.

Before concluding that the lack of the predicted effects undermines the action potentiation hypothesis, it is necessary to examine a possibly serious confound present on most trials of the experiment. This arises from the relation between the position of the response (cued by the objects inversion) and the position of the object feature that conveyed the most information about object inversion. Most of the objects used in the study had long principle axes, at one end of which lay the functional part[10]. This end of the objects also contained most, if not all, the information about inversion. A spoon or spatula is a typical example. If the serving spoon is placed horizontally in front of the two hands with the handle to the right (see Figure 4.8) the part that conveys information about object inversion is on the *left* side whereas it affords grasping by a *right* hand reach.

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[10] The objects were chosen with two aims in mind. First they had to be easily identifiable as upright or inverted as well as having an opposition axis whose orientation would affect the relative affordance for grasping by the right or left hands. Second they had to be easily manipulated by the experimenter. This latter requirement resulted in most of the objects being of the type described above, see Table 4.3.

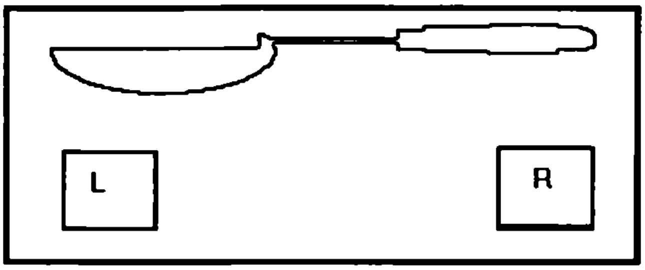


Figure 4.8. Schematic diagram showing a typical (upright) object in Experiment 2.

The presentation of an object that affords a right hand grasp, such as the spoon in Figure 4.8, requires directing attention to the left side of space and vice versa. Thus left-right graspability is always opposite to the left-right side of space in which information about object inversion is contained. Any effect of codes for the affordance for grasping by a particular hand may therefore be cancelled out or overridden by opposing left-right codes based on the position of relevant object part. This explanation is, of course, post hoc, but corresponds exactly to attention shifting accounts of the Simon effect. Stoffer & Yakin (1994), for example, give evidence that horizontal (as opposed to zooming) attention shifts are required for the Simon effect to occur. In the present experiment the last attentional movement before response determination, would be a horizontal attention shift in the opposite direction to the left-right status of the objects' affordance for grasping. Directing attention to the relevant object part not only would therefore result in a code of opposite value (along the binary left-right dimension) to that induced by the objects affordance, but also could have the additional effect of reducing the information available about the objects affordance. In chapter 2 it was pointed out that attention probably plays a critical role in directing visual to motor transformations (e.g., Stein, 1992). For the actions an object affords to be potentiated requires that the object be attended to. If task demands restrict the attentional focus to a limited part of the object it makes it likely that any actions potentiated would reflect this restricted part of the object. Any motor patterns activated by the structure of this part of the object would not be characterised according to left-right 'graspabilty', but instead reflect components such as grip type.

4.4. General Discussion

Experiment 1 showed that the orientation of common graspable objects influences the speed with which a reach and grasp movement can be initiated. The layout of Experiment 1 was designed to maximise this effect along a left-right dimension. The hands were both free and located to the left and right of the body midline and the objects were centrally placed. Under these conditions reaching and grasping movements by a particular hand were facilitated when the object was oriented toward that hand. This effect was most prominent for the dominant (right) hand. The relation between hand choice and object orientation shows a similar pattern to that reported by Klatzky et al. (1995) on grip type and object shape. For both components of prehension *initiation* times are affected by the compatibility between the required response and the object characteristic.

Effects on initiation times, rather than movement time, do not prove that these components of prehension are partially activated by the visual properties of the object even before responses have been cued. They do show, however, that such components are planned before the response is executed. As mentioned in the discussion of Experiment 1 there are two possible mechanisms whereby the object could exert an effect on initiation times. The first assumes that the visual properties of the object automatically activate components of compatible responses. When the required response is determined, from an action-irrelevant object property (colour in Klatzky et al.'s (1995) study and tone in Experiment 1), then response times will be speeded on compatible trials and hindered on incompatible trials. The second possibility assumes that the visual properties of the object do not activate any components of the actions afforded by it. Only after the required response has been determined do the visual properties of the object exert an effect. On this account the visual properties of the object, and thus the compatibility relations also, only influence the action system once a decision to make a specific response has been chosen. It is argued here that the structure of the visuo-motor system make the first proposal most likely. The second mechanism may also contribute to the effects given that the two processes are not mutually exclusive. Either way the fact that object orientation significantly affects movement initiation times on bi-manual reaching and grasping movements suggests that it is a strong candidate for a component of action that is activated simply by viewing the object. This was tested in Experiment 2.

The results of Experiment 2 did not support the action potentiation account. The task-irrelevant orientation of common graspable objects had no effect on left-right key press responses when these were cued by object inversion. This was the case whether the object was viewed within or beyond the reaching space. Given the results of the first experiment one would expect object orientation to influence left-right responses if the actions afforded by the object were being potentiated merely by attending to it. Although simple key press responses do not correspond to the reaching and grasping action investigated in Experiment 1, they nevertheless, share a component of that response, namely, left-right hand selection. Thus the potentiation of a reaching and grasping response would be expected to facilitate even key press responses by the hand in the best position to perform that action. Unfortunately the data do not allow a true test of the hypothesis for reasons stated in the discussion. Using object inversion as the criteria for determining response led to the possibility that any left-right codes based on the potentiated action would always be opposed by left-right codes based on the directing of attention to the critical object region. Such attentional focusing would also lessen the likelihood of potentiating the action because the object properties responsible for determining the reaching affordance were not in this location.

In order to provide a better test of the object potentiation hypothesis the next experiments used objects whose inversion was determined by more global object properties.

5. Chapter 5: Bi-manual versus Uni-manual responses to oriented objects.

5.1. Outline

Because of the possibility that the effects of action potentiation in Experiment 2 were being cancelled out by opposing response codes based on the directing of attention to the relevant region of the object, Experiment 3 used stimuli whose inversion was characterised by more global properties. For practical reasons this meant that photographs of real object were used as stimuli. Object inversion was still used as the criteria for selecting left and right key press responses as this is an object property that requires processing to a level sufficient to extract the properties that also influence the actions the object affords (contrast this with colour for example). Apart from the change to transparencies of objects and the use of a single distance, Experiment 3 was identical to Experiment 2. The results were very different however. Despite object orientation being irrelevant to the selection of a left-right key press response it exerted a small but highly significant effect on the speed with which these responses were executed. Right hand responses were faster when the objects were oriented to the right than to the left whereas left hand responses were executed faster when the objects were oriented to the left compared to the right. The magnitude of the effect was similar for both left and right responses. The results are consistent with the action potentiation account. Even though no reaching and grasping responses were called for, right hand responses were facilitated by objects that afforded a reach and grasp movement by the right hand whereas left hand responses were facilitated by objects that afforded a left hand action.

Experiment 4 aimed to rule out the most plausible alternative explanation of the effect. This explanation is based on the notion of Dimensional overlap (Kornblum et al. 1990). The design of Experiment 3 could be classified as a Type 3 SRC ensemble in Kornblum et al.'s terminology, in which there is dimensional overlap between the irrelevant left-right orientation of the stimulus set and the relevant left-right response dimension, but no overlap between the relevant stimulus dimension (object inversion) and the responses. According to this model the compatibility effect amounts to a Simon effect of object orientation and has nothing to do with the actions afforded by the object. It arises from the 'left-right' coding of the stimuli and the subsequent automatic activation of the corresponding left-right response code. If this was responsible for the effect observed in Experiment 3 it should also be found when the responses do not bear a meaningful relation to the actions afforded by the objects, but still maintain the required relative left-right dimension. Experiment 4 repeated Experiment 3 using uni-manual left-responses. The results were clearly in favour of the action potentiation account. In the uni-manual condition no compatibility effect of object orientation on left-right responses was observed. This further supports the view that the critical relation for the compatibility effect in Experiment 3 was between the action relevant object properties and the component of action responses. It also undermines the view that dimensional overlap existed in Experiment 3. It would appear that object orientation, *per se*, does not produce automatic left-right stimulus codes. The left-right element in the compatibility effect arises from the involvement of the action system.

5.2. Experiment 3: The priming of hand of response by object orientation.

5.2.1. Introduction.

The rationale behind this experiment was the same as that of Experiment 2 but with some important modifications in the stimuli. These were chosen so that decisions regarding their inversion were unlikely to involve directing attention to a limited region of the object (see Table 5.1). The features that go toward determining whether a kettle, for example, is upright or inverted are much more widely distributed than a serving spoon or spatula. When the required response is selected, attention is likely to be directed to the whole object rather than a small part of it. As a result the object properties that determine the relative affordance for grasping by a particular hand will also be subject to visual attention at the time the response is determined and no opposing codes, based on the direction of attention shifts, should be present. Consequently any compatibility effects arising from potentiation of components of action should be more easily detected.

5.2.2. Method

Subjects

Thirty subjects took part in the experiment. All were students at the University of Plymouth and received course credit for their participation. All subjects had normal or corrected to normal vision and were naive as to the purpose of the experiment. All except two subjects were right handed by self report.

Apparatus and Materials

Black and white transparencies of twenty two graspable household objects made up the stimulus set. All the objects were capable of being grasped and manipulated by one hand and were photographed in two horizontal orientations (one compatible with a right hand grasp the other with a left hand grasp) and two vertical orientations (upright and inverted). There were thus 22 x 2 x 2 = 88 slides which were back-projected onto a translucent screen (46 x 46 cm) from two Kodak carousel random access projectors, modified to allow millisecond shutter control. The stimuli used are listed in Table 5.1. Subjects were seated with their head 45 cm in front of the screen and the index finger of each hand resting on two response buttons 30 cm apart and 15 cm in front of the screen. The objects were photographed so as to appear as if they were resting on the table at the position of the screen at approximately their actual size at a distance of 50 cm. They subtended visual angles of between 11 to 18 degrees.

Table 5.1. List of objects used in Experiment 3.

Iron	Teapot
Kettle	Coffee pot
Large jug	Glass saucepan
Saw	Electric carving knife
Saw	Frying pan
Sieve	Handled dustpan
Dustpan and brush	Metal saucepan
Frying pan	Glass coffee pot
Medium jug	Decorative jug
Plant waterer	Iron
Kettle	Plastic Jug

Design and Procedure

The experiment consisted of two blocks of 176 trials in which each object appeared twice in each horizontal and vertical orientation. Subjects were instructed to make push button responses with the left or right hand depending on whether the object was upright or inverted. The actual mapping of response hand to object inversion was blocked and pseudo randomized so that an equal number of subjects received each mapping in the first block. For most objects whether it was upright or inverted needed no definition for the subjects. In the case of objects such as a knife or saw, subjects were told that upside down was defined with regard to the objects normal use. Thus objects such as a saw or a knife were photographed with the blade at right angles to the resting surface rather than lying flat. The saw was therefore upside down when the teeth were pointing up rather than down. Subjects experienced no difficulty in understanding this definition of inversion. The left-right horizontal orientation of the object was irrelevant to the response. Subjects were instructed to respond as fast as possible whilst maintaining accuracy. Slide order was randomized for each subject and the experiment was run, and response latencies recorded, on an Acorn Archimedes computer. Each subject received twenty practice trials before each block. A trial began with the appearance of an object on the screen and ended when a response had been made or three seconds had elapsed. The objects remained in view until a response was made. There was a 4 second delay between the end of one trial and the beginning of the next. Subjects were not given feedback on response latencies but errors were immediately followed by a short tone from the computer.

5.2.3. Results

Response times

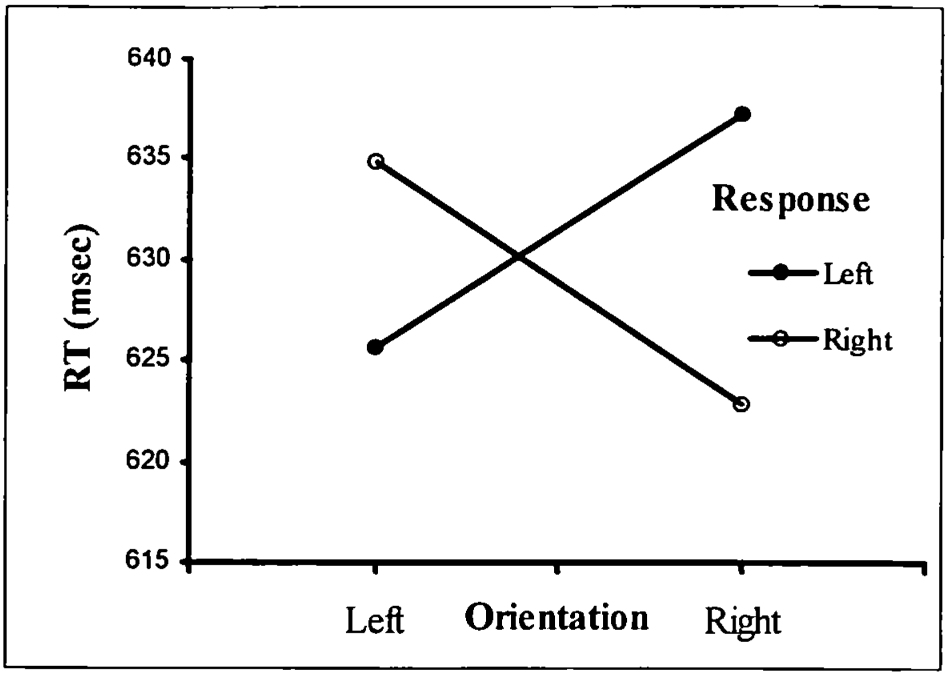
Two subjects were removed from the analysis as their error rates exceeded 10%. For the rest condition means were obtained after removing reaction times greater than two standard deviations from each subject's overall mean. A within subjects ANOVA was carried out on these means with the factors object orientation (left or right), mapping (right response for upright objects, left hand for inverted (RH_UP), left response for upright objects, right for inverted (LH_UP)) and response (left or right). The effect of mapping was significant with the RH_UP mapping producing faster average response times (M=612.70 than the converse LH_UP mapping (M=647.57), [$F_{(1,27)}$=7.54 p= 0.011]. In addition there were significant interactions between mapping and response and between response and object orientation. Right hand responses in the RH_UP mapping (M=602.8) were on average 20 msec faster than left hand responses (M=622.7). In contrast in the LH_UP mapping left hand responses (M=640.14) were on average 15 msec faster than right hand responses (M=655.0), [$F_{(1,27)}$ =9.12, p=.005]. The effect of most interest is the interaction between object orientation and hand of response. When the irrelevant orientation of the object was congruent with the hand of response, determined by the object's inversion, responses were faster than when it was incongruent. Thus right hand responses were faster when the object was depicted oriented to the right (M=622.9) than when to the left (M=634.8), whereas left hand responses were faster when the object was oriented to the left (M=625.6) compared to the right (M=637.2); [$F_{(1,27)}$=19.13, p<.001], see Figure 5.1 and Table 5.2. Individual Pair-wise comparisons using t tests indicated that the compatibility effect of object orientation was significant for both left and right responses. For right handed responses t=3.13, and for left hand responses t=3.06, [$t_{(.05,27)}$=2.052].

Error rates

Analysis of subject error responses showed a similar pattern of results to the response latency data. The effect of mapping approached significance with fewer errors made in the RH_UP mapping (M=4.6) than in the LH_UP mapping (M=5.8), [$F_{(1,27)}$=3.92, p=.058]. The only other significant effect was the interaction between object orientation and response, with fewer errors made for right hand responses when the object was oriented to the right (M=4.8) rather than the left (M=6.1), and similarly for left hand responses fewer errors were made when the object was oriented to the left (M=3.8) than to the right (M=6.2), [$F_{(1,27)}$ =14.52, p=.001]; see Figure 5.1. The pattern of error responses show no indication of any speed-accuracy trade off for this interaction.

Table 5.2. Mean RTs, standard deviations and (% errors) for Experiment 3 by response and object orientation.

	Response	
Orientation	**Right**	**Left**
Right	**622.94** 103.91 (4.76)	**637.20** 106.32 (6.24)
Left	**634.82** 104.86 (6.07)	**625.59** 103.69 (3.82)



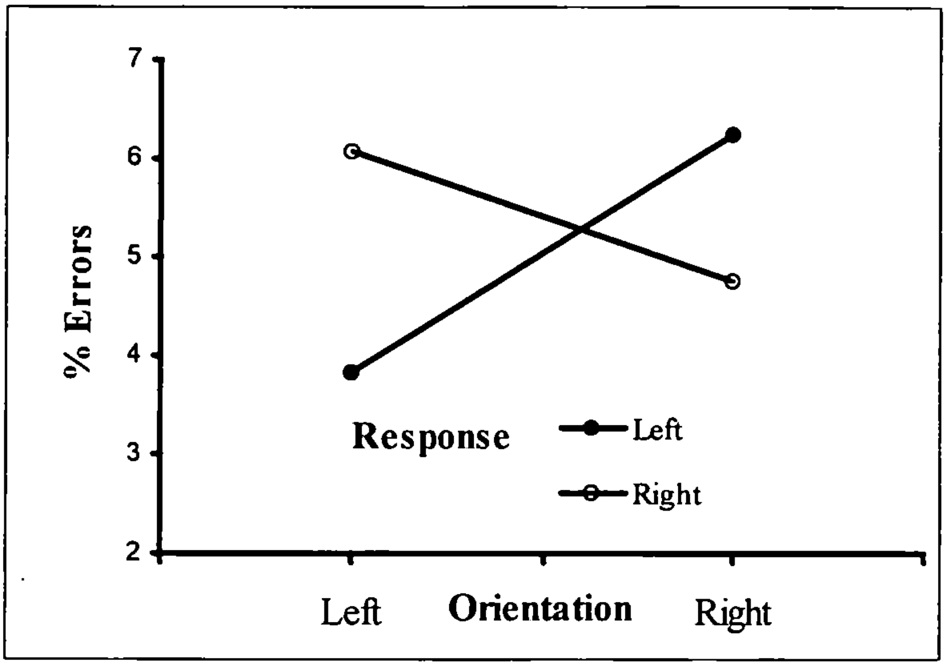


Figure 5.1. Mean correct response times and error rates for Experiment 3 by response and object orientation. All response times in msec.

Materials analysis.

An ANOVA was carried out on the data with objects as a random factor and condition means obtained by averaging over objects and across subjects. This yielded a similar pattern of results to the subjects analysis. The effect of mapping was significant with response times fastest in the RH_UP mapping (M=617.9) compared to the LH_UP mapping (M=651.6), [$F_{(1,21)}$=61.45, p<.0001]. Both interactions observed in the subjects analysis were also observed in the materials analysis and had similar patterns. The interaction between response and mapping was significant [$F_{(1,21)}$=5.21, p=.033] as was that between response and object orientation [$F_{(1,21)}$=27.74, p<.001]. To determine the extent to which the effect of most interest (the interaction between response and object orientation) would generalize to both a new set of objects and subjects simultaneously F*min*[11] (Clark 1973) was computed. This gave a significant result: [$Fmin_{(1,48)}$=11.32, p<.01], indicating that the effect observed was highly unlikely to be restricted to the sample of objects (and subjects) used in the study.

Supplementary Analyses

Separate ANOVAs on the subject data using mean median RT and mean LOG(RT) both gave significant results for the interaction between object orientation and response and displayed very similar patterns to that using two standard deviation cutoffs. Using mean Median RT [$F_{(1,27)}$=9.14, p=.005] and using mean LOG(RT) [$F_{(1,27)}$=10.34, p=.003].

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[11] F*min* gives a conservative test of the ability of an observed result from an experiment involving two random factors to generalise simultaneously to a new sample of both of the random factors (in this case a new sample of subjects and objects). The procedure for calculating F*min* is given in Appendix 1.

5.2.4. Discussion

Experiment 3 showed that the left-right orientation of common graspable objects had a significant effect on the speed with which a particular hand made a simple push button response, even though the horizontal object orientation was irrelevant to response determination. The orientations of the objects were chosen so as to make them preferentially compatible with a reach and grasp movement by the left or right hand. When the required response, determined by the mapping condition and the inversion of the object, was with the right hand, response times were shorter, and errors fewer, when the object's horizontal orientation was also compatible with a right hand reach and grasp movement. Similarly left hand responses were faster when the object was compatible with a left hand grasp. This supports the proposal that certain action related information - in this case the hand most suited to grasp the object - is represented automatically when the object is viewed in the peripersonal space. The data, do not, of course, rule out other explanations. In particular, it is possible that object orientation was automatically assigned an abstract spatial response code and that this was the basis for the observed effects. In this case the results could be interpreted as a Simon effect of an irrelevant spatial stimulus dimension, consistent with Kornblum et al.'s (1990) dimensional overlap model of SRC - the experiment could then be classified as a Type 3 ensemble in their terminology. A Type 3 ensemble has dimensional overlap between the irrelevant stimulus dimension (object orientation in this experiment) and the response, and no dimensional overlap between the relevant stimulus dimension (object inversion) and the response. In fact the main effect of response mapping (right hand responses to upright objects and left hand responses to inverted objects were on average 34 msec faster than the reverse mapping) does appear to be a standard SRC effect. Although here there was no overlap between the stimulus and response dimensions, Weeks & Proctor (1990) have proposed a salient features model of SRC effects to account for the existence of compatibility relations between such orthogonal dimensions. In this account response times will be shortest when the required mapping matches the relative salience of the stimulus and response dimensions. This would account for the mapping effect observed here, given that an upright object and a right hand response represent the salient features of the stimulus and response sets respectively. The abstract nature of such saliency codes is necessitated by the lack of any physical overlap between the two dimensions.

For the effect of horizontal object orientation however, there is the possibility that this is coded as 'left' or 'right', thereby overlapping with the response dimension. If the results of previous SRC research reflect cognitive mechanisms capable of generalizing to more complex stimuli, then such an abstract level of coding may well be entering into the observed effect. However this does not rule out the possibility that response codes at a less abstract level, are also generated automatically when the stimuli are meaningful and vary along dimensions important in determining the way we interact with them. The properties of a visual object represented by the (dorsal) visual system are precisely those needed to successfully prepare and guide actions. It would seem likely, therefore, that any codes generated automatically by a visual object would contain information about the relation of the object to the motor system of the observer.

One way of clarifying the relative contributions of abstract spatial coding of orientation along a left - right dimension and the automatic activation of a response code, based on the hand most suitable for grasping the object, is to repeat Experiment 3 in a uni-manual version. The importance of relative, rather than absolute, spatial coding in obtaining standard compatibility effects is well attested to in the literature (see e.g., Proctor & Reeve 1990, Umiltà & Nicoletti 1990). If object orientation was being coded along an abstract left-right dimension and this was responsible for the automatic generation of a left-right response code, then the same pattern of results should be obtained when the response is a left-right finger press of a single hand. Comparing the effect of a *relevant* location dimension between a bi-manual and uni-manual SRC task, Shulman & McConkie (1973) found that the compatible mapping produced an advantage of the same magnitude in both conditions. Thus it would seem reasonable to suppose that when abstract left-right codes are producing compatibility effects the nature of the left right responses is not crucial to the magnitude of the effect - at least with respect to relevant stimulus dimensions. If, on the other hand, the effect was solely produced by the activation of a response based on the hand most suitable for grasping the object, then the effect should be much smaller or absent in the uni-manual condition.

5.3. Experiment 4: Object orientation and uni-manual responses.

5.3.1. Introduction

The effect of object orientation on response latencies in Experiment 3 is consistent with an account based on the automatic activation of a response from the abstract left-right coding of the object's horizontal orientation as well as with one based on the object's grasp compatibility. If the effect is due solely to the former then dissociating the left-right response positions from the effectors used to implement them should have little effect on the pattern of results. Experiment 4 was designed to provide a means to compare the relative contribution of abstract coding and action potentiation to the effect observed in Experiment 3. This assumes that left-right object orientation has no preferential effect on the actions that can be carried out by the index and middle fingers of the right hand.

5.3.2. Method

Subjects

Thirty subjects, all students at the University of Plymouth, took part in the experiment. All had normal or corrected to normal vision and had not participated in the first experiment. They were paid £3.00 for participating. All subjects were right handed by self report.

Apparatus and Materials

The stimulus materials were identical to those used in Experiment 3 except that two objects, (nos. 2 and 5 in Table 5.1), were removed from the set as one slide had been damaged. A total of eight slides had to be removed to keep the stimulus set balanced. This meant that the total number of trials per subject was reduced from 176 to 160. The only other difference was that responses were executed on a single device operated by the index (left response) and middle (right response) fingers of the right hand. The two response buttons were 2.5 cm apart and positioned centrally 15 cm in front of the viewing screen.

Procedure

The procedure was identical to that of the Experiment 3 except that subjects were instructed to make responses with the index and middle fingers of their right hand.

5.3.3. Results

Response times

Response times greater than two standard deviations from each subjects overall mean, and errors, were excluded from analysis. An ANOVA was carried out on subjects condition means with the factors response (Left or Right finger), mapping (right finger for upright objects, left for inverted (RF_UP) or the reverse (LF_UP)) and object orientation (Left or Right). This yielded one significant result - the interaction between response and mapping, also observed in Experiment 3. In the RF_UP mapping right finger responses (M=609.3) were on average 9.2 msec faster than left finger responses (618.5), whereas in the LF_UP mapping left finger responses (M=605.6) were on average 22.6 msec faster than right finger responses (M=628.2); [$F_{(1,26)} = 15.53$, $p=.001$]. Most importantly the interaction between response and object was not significant [$F_{(1,26)} = 1.61$, $p=.215$] and showed no similarity to the effect observed in Experiment 3 (see Figure 5.2 and Table 5.3).

Error rates

Analysis of subjects error data showed a single significant effect of object orientation. Subjects made fewer errors to objects oriented to the left (M=3.5%) than to the right (M=4.5), [$F_{(1,26)}$ =8.8, p=.006]. The interaction between object orientation and left-right finger response did, however, approach significance (see Figure 5.2). For right finger responses there was hardly any difference in error rates between right (M=4.0%) and left (M= 3.9%) oriented objects. For left finger responses, however, fewer errors were made to left oriented objects (M=3.1%) than to right oriented objects (M=5.0%), [$F_{(1,26)}$ = 3.51, p=.072].

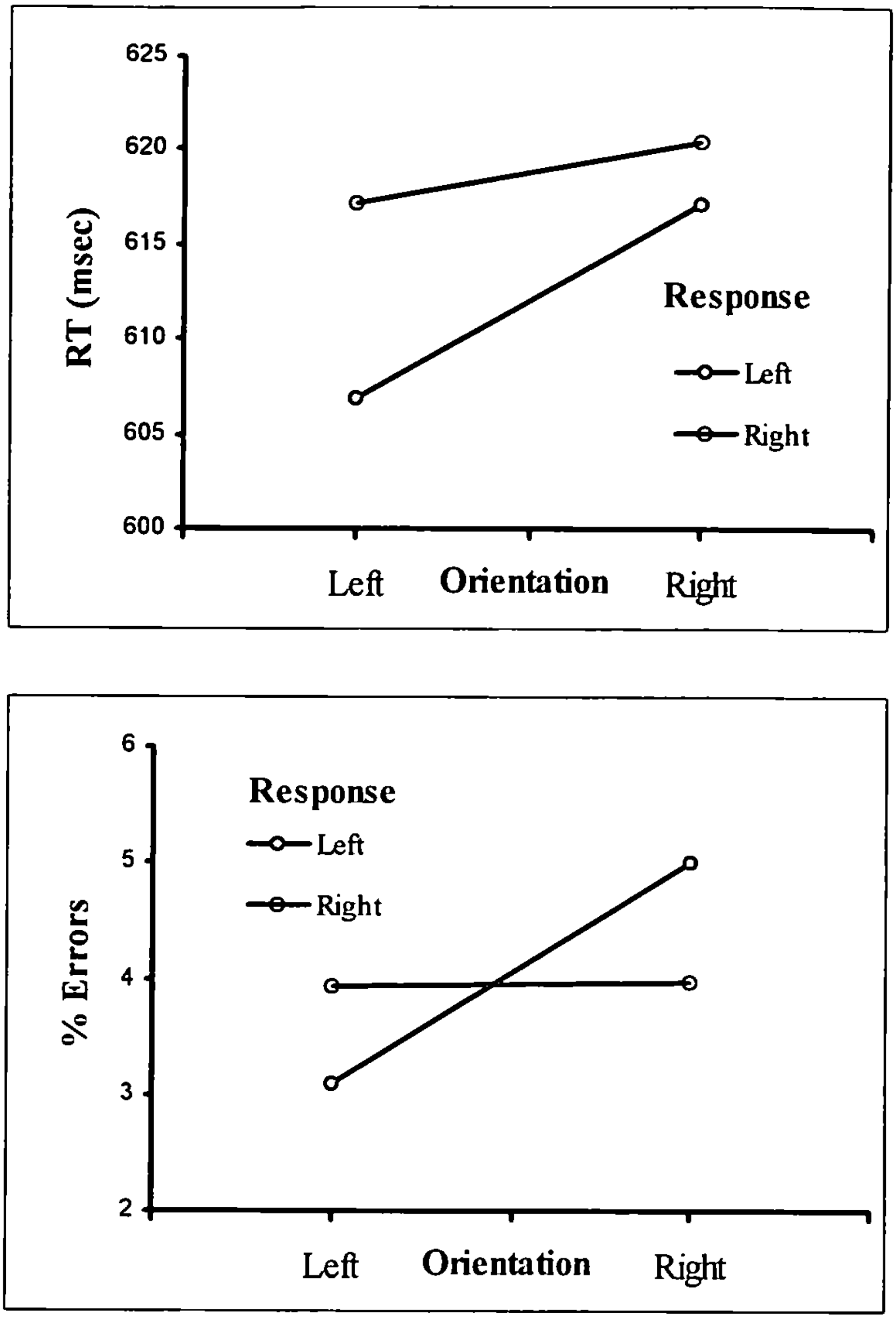

Figure 5.2. Mean correct response times and error rates for Experiment 4 by response and object orientation. All response times in milliseconds

Table 5.3. Mean RTs, standard deviations and (% errors) for Experiment 4 by response and object orientation.

	Response	
Orientation	Right	Left
	620.41	**617.21**
Right	119.61	112.01
	(3.98)	(5.0)
	617.11	**606.88**
Left	112.22	96.76
	(3.94)	(3.10)

Materials analysis.

Analysis of the data using objects as a random factor showed a similar pattern of results to that of the subjects analysis. The only significant effect was the interaction between response and mapping with right finger responses in the RF_UP mapping (M=612.0) producing faster response times than left finger responses (M=620.6), whereas in the LF_UP mapping left finger responses (M=608.9) were faster than right finger responses (M=628.8), [$F_{(1,19)}$=5.22, p=.034]. The effect or response approached significance, with left finger responses (M=614.7) producing on average faster response times than right finger responses (M=620.4), [$F_{(1,19)}$= 4.24, p=.053] - a pattern which can be seen in Figure 5.2

Supplementary Analyses.

As in the previous experiments the subject data was also analysed using mean median response times and mean log response times. Analysis using Log RT showed a similar pattern to that using 2 standard deviation cut-offs. The only significant effect was the interaction between response and mapping [$F_{(1,26)}$= 20.1, p<.001]. Analysis using medians, however, found both this interaction [$F_{(1,26)}$=17.5, p<.001] and the interaction of most interest, between response and object orientation, to be significant [$F_{(1,26)}$= 5.18, p=.031]. The pattern of means in both cases were identical to those shown in figure 4.2. Because of the result of the analysis using medians a materials analysis on median response times was also carried out. This produced a result similar to the other analyses - the interaction between response and object orientation was not significant [$F_{(1,19)}$ = 1.68, p=.210].

5.3.4. Discussion

As in Experiment 3 the interaction between response and mapping is most readily understood as the effect of object inversion, responses to upright objects (the combined conditions of right responses in the RF_UP mapping and left responses in the LF_UP mapping) producing, on average, response times 16 msec faster than inverted objects. The most important result of Experiment 4 is that the compatibility effect of object orientation on the hand of response observed in Experiment 3 was not found when left-right responses were executed by the index and middle fingers of a single hand. The statement that there was no evidence for this effect must be treated with *some* caution given the significant effect observed using mean median response times. However both the supplementary analyses and the lack of a significant interaction for the materials analyses using medians strongly suggest that this compatibility effect is restricted to the condition in which responses are executed by the left and right hands rather than the fingers of a single hand. In addition the pattern of means for Experiment 4 do not show the clear relation between left-right response and left-right object orientation observed in Experiment 3.

In order to confirm the difference between the compatibility effect across both experiments a further analysis of variance was carried out using the data from both experiments and with experiment as a factor. One randomly assigned subject[12] was removed from the Experiment 3 data to ensure the nesting of subjects within experiments was balanced. This analysis revealed two main results regarding the interaction of interest. First the pooled data still showed a highly significant interaction between left-right response and left-right object orientation [$F_{1,52} = 14.84$, $p<.001$]. Second and most important there was a significant interaction of this effect with Experiment [$F_{1,52} = 4.25$, $p=.044$], the breakdown of which corresponds to the original separate analyses carried out for the two experiments. The analysis therefore confirms the difference of the compatibility effect across these two experiments - it occurs with bi-manual responses but not with uni-manual responses.

5.4. General Discussion

That the compatibility effect of object orientation and left-right response is restricted to the bi-manual condition is not consistent with abstract cognitive coding accounts of SRC. In the second experiment the responses were still defined by a left-right dimension. If the compatibility effect in Experiment 3 was due to correspondence between the left-right codes of the response and an automatically activated left-right stimulus code, based on orientation, it should also have been observed in Experiment 4. That it was not implies that the state of

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[12] In this case subject no. 5 was removed

the response system had a differential effect on the codes generated during the task. Importantly, in both experiments left-right *response* codes would have been generated by the combination of mapping rule and object inversion, as this was the explicit task. The left-right nature of the response in both experiments would, therefore, enable a left-right response code to enter into compatibility relations with any stimulus codes. In Kornblum et al.'s (1990) model of SRC a stimulus property automatically generates a further response code whenever there is dimensional overlap between this property and the response dimension. It is not clear, however, whether object orientation actually does overlap with the left-right spatial dimension of the response. Indeed this is one of the problems of the concept of DO itself. Assuming that the DO model is correct then compatibility effects will arise if there is DO between the response dimension and one of the stimulus dimensions whether relevant to response determination or not. The lack of this effect in Experiment 4 therefore implies that no (or at least very little) DO exists between object orientation and the left-right dimension of the responses. This implies that the compatibility effect observed in Experiment 3 did not arise from the congruency relations between object orientation and left-right responses, for these relations were identical in Experiment 4. Instead the results are consistent with the notion that motor patterns associated with the actions the objects afford are activated even when explicit actions are not part of the task demands.

Cognitive codes and SRC

The results of Experiments 3 and 4 have implications for coding accounts of SRC. Cognitive codes form an integral part of most explanations of S-R compatibility effects. Precisely what is meant by the term is seldom, if ever, made explicit. They are assumed to arise from a conceptualisation of the task structure. With the relevant task variables, that is those that enter into the mapping rule, the relevant properties of the task are given to the participants. They can then function as signs or 'labels' that form the basis of a decision process that results in the selection of the required response. The action system only enters the relation in a trivial sense - only after the decision has been made to press the right hand key, say, must the appropriate muscle commands be generated to implement this. These codes are, therefore, abstract and relatively high level in as much as they have no basis in the motor system. They exist at the level of rule based decision processes only. With irrelevant stimulus dimensions it is harder to see how and why codes are generated at this same abstract level *automatically*. Notions such as dimensional overlap attempt to explain their generation by asserting that similarity between response and stimulus 'dimensions' leads to some sort of cognitive match or mismatch between response and stimulus codes. In the case of the Simon effect both stimuli and responses have a (horizontal) spatial dimension. The compatibility effect is assumed to arise because the overlap in dimensions results in the spatial code of the stimulus activating the spatial code of the response, and therefore the response itself. The latter is then executed faster on congruent trials because it is already activated. The automatic response activation again has nothing to do with the action system. An automatically generated stimulus 'label' simply shares the same label type as the responses - left or right in the case of the Simon effect. However the process by which the irrelevant stimulus property is so coded is still left unexplained. As pointed out in Chapter 3 attempts to explain the basis of such codes have involved the attention system, specifically the formation of saccade commands (Nicoletti & Umiltà, 1989, 1994, Stoffer & Yakin, 1994). A saccade command itself however, does not contain any left or right labels. It merely consists in the motor commands necessary to bring the fovea to the vicinity of the stimulus. Once detailed attention is paid to the reasons for coding, even in abstract displays, the action system does appear to play a central role. As Stoffer & Yakin (1994) observe it is the organisation of the visual attention system that makes such codes possible. They are not abstract at all, in the sense of being removed from the action system, but tightly bound to it. According to this view, dimensional overlap in the Simon paradigm turns out to be dependent on the common representational framework employed by the visual attention system and the motor system. They do not overlap merely because of some kind of conceptual or structural similarity. Structural similarity may well be present but it is not on account of this that the congruent response is automatically activated.

Whenever an action afforded by an object can be described across a left-right dimension a case can almost always be made for the existence of cognitive codes that reflect this description. It is a mistake however, to conclude from this that such codes necessarily are formed and, even if formed, are the causal basis of compatibility effects for congruent responses. The results of Experiment 4 are pertinent here. Because object orientations can be chosen that afford reaching responses by either the left or right hand it might proposed that this left-right distinction is reflected in the visual properties of the objects. However this distinction into left and right orientations is only fully recoverable once the rule for assigning objects into the two categories is known. Why, after all, should a kettle with the spout pointing towards the left be coded as 'right oriented' rather than 'left oriented' if no information about the relevance of graspability is given. The lack of a compatibility effect of object orientation in Experiment 4 confirms that left-right stimulus codes were not in fact generated by the purely visual properties of the objects. Nevertheless at some level a code having a left-right distinction must have been present in Experiment 3 to account for the compatibility effect observed. If it did not reside in the visual properties of the stimuli it must have been present at the level of the responses. There is no need to invoke any left-right codes over and above the actual potentiation of the hand most suited to perform the action the object affords. The code is a motor pattern itself rather than an abstract description of one of the characteristics of the action the motor pattern corresponds to.

The results of Experiment 3 represent the first case of a compatibility effect of an irrelevant stimulus property to have been shown from a set of natural stimuli. The property responsible for the effect was not a fixed binary feature of the stimulus display. Objects did not simply appear either to the left or right of some fixation point. This reduced the possibility of binary spatial stimulus codes being automatically generated on account of a salient spatial feature. The results of Experiment 3 do not reflect coding at the level of the stimulus. At this level there is no clear division into left and right stimuli. Only by taking account of the actions the objects afford does a consistent left-right categorisation become apparent. Object orientation is only one of many object properties that influence affordances. The next chapter examines the role of different stimulus-response relations on action potentiation.

6. Chapter 6: Further evidence for the potentiation of actions by visual objects: Wrist rotation and precision-power grip responses in SRC tasks.

6.1. Outline

The use of the SRC paradigm to investigate action potentiation by visual objects requires that responses consist of a *component* of an afforded action. This requirement arises from two considerations, one practical and the other methodological. For practical reasons a complete action such as a reach and grasp movement is not always easy to use as a response measure. More importantly, getting subjects to make such a response would almost certainly disrupt the requirement that subjects were naive to the relation between their responses and the objects viewed. This is important, as a true test of the proposal that actions are potentiated by visual objects simply by viewing them requires that subjects are not led explicitly to imagine interacting with them.

The first three experiments of this chapter explored the wrist rotation component of reaching and grasping movements. This component is a requirement for a successful reach and grasp movement in that it enables the hand to correctly align with the opposition axis of an object. It is also suitable in that it can be readily categorised along a binary response dimension - clockwise or anti-clockwise rotation from a suitable starting position - a characteristic that, like hand selection, enables its use in a choice RT paradigm. The first experiment used a paradigm very similar to that employed in the previous experiments. Subjects were required to make clockwise or anti-clockwise wrist rotation responses to objects depending on the objects' inversion. The objects themselves would either require a clockwise or anti-clockwise wrist rotation if they were to be grasped from the start position. Like object orientation in the previous experiments, this property was irrelevant to the task but was expected to influence response times depending on whether or not the cued direction of response was compatible or incompatible with the object. No compatibility effect was found, although there was an interaction between mapping and object type. A close consideration of the objects and responses does, in fact, suggest that this interaction reflects the affordances for grasping generated by the stimuli. Object inversion was used to cue the direction of response, as in Experiments 2-4, but in this case could be argued to affect the actual affordances of the objects. The data do in fact fit quite well with an account that takes into consideration the fact that some objects, when inverted, require grasping in a manner that employs a wrist rotation of opposite direction to that used when they are upright. This explanation is based on the 'end state comfort effect' Rosenbaum et al., (1990)). Experiments 6a and 6b examined the same wrist rotation responses to objects that were always upright and when the direction of wrist rotation response was cued by a high or low pitched tone stimulus. Subjects had to attend to the objects because the Experiments were set up under the guise of a recognition memory task. When the cue was given immediately after object illumination no compatibility effect was found. In contrast, when the tone cue was given, and responses executed, whilst the objects were still in view a marked compatibility effect was observed. Although a comparison of the data from both experiments failed to show a significant difference between the two response conditions the data nonetheless point to the importance of an active visual representation of the object for obtaining the compatibility effect. It is argued that this likely reflects the transient, rapidly updated, representations employed by the dorsal visuo-motor stream. The final experiment examined the potentiation of grasp types by visual objects compatible with either precision or power grips. Responses mimicked precision or power grips and were cued by tones given during object exposure. A marked compatibility effect was observed, although only significant for power grip responses.

6.2. Experiment 5 : Object type and wrist rotation responses

6.2.1. Introduction

Experiments 1-4 manipulated the left-right orientation of an object in order to affect its grasp compatibility. Choosing which hand to reach for an object is only one aspect of a process that results in an object being grasped. Orientation, object size and the position of the opposition space in the object, all influence the way the hand must approach the object. In order to successfully grasp an object the hand must be rotated to bring the fingers in line with the opposition space (Iberall, Bingham & Arbib, 1986; Arbib, 1990a, 1990b; Jeannerod, 1981; Jeannerod, Paulignan, Mackenzie & Marteniuk, 1992). In Experiment 5 the wrist rotation component of reaching and grasping was used to further examine the response codes activated by visual objects.

Categories of objects can be formed on the basis of the way the wrist needs to rotate from a neutral orientation in order to form a stable grasp. If the initial orientation of the wrist is such that the thumb is aligned at the 11 o'clock position tall cylindrical objects, when vertically oriented, require a clockwise wrist rotation to bring the hand into alignment for a suitable grasp. The reverse direction of rotation is required for horizontally oriented objects or for any object small relative to the hand. The 11 o'clock position of the thumb is neutral in the sense that the wrist has a natural tendency to return to this orientation (see Rosenbaum, Marchak, Barnes, Vaughan & Jorgensen, 1990), and can exert the greatest torque from this position. Examples of the two directions of wrist rotation would be reaching and grasping an upright wine bottle (clockwise rotation) and grasping a knife resting on a table at approximately right angles to the line of sight, with the handle to the right (anti-clockwise rotation). If the wrist of your right hand is positioned in front of you, with the thumb aligned at the 11 o'clock position, in order to reach for and grasp the wine bottle it must rotate in a clockwise direction to bring the fingers and thumb into the correct position to achieve a stable grasp. In contrast, if you were to reach for and grasp the knife, the wrist needs to rotate anti-clockwise in order to achieve the grasp. In this experiment two sets of objects were used - one set would require a clockwise wrist rotation from the neutral start position to achieve a stable grasp, the other set would require an anti-clockwise rotation (see Table 6.1 for a list of objects used). Unlike the previous experiments object *orientation* was not manipulated. Many of the objects used, such as bottles or jars, did not posses a left-right horizontal orientation at all. Those that did, such as a jug or a spoon, were always oriented with the handle to the right (as responses were always executed by the right hand). The compatibility relation was determined by the direction of wrist rotation needed to grasp the object and the direction of rotation cued by the inversion of the object[13] given one of the two mapping rules.

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[13] In fact, and a point taken up in the discussion, using object inversion to cue *wrist rotation* responses results in an ambiguity in the affordances offered by the object. The central point is that for some objects (e.g. a bottle) their physical shape when inverted affords a clockwise wrist rotation, merely to be grasped, but an anti-clockwise rotation if they are to be grasped in order to be returned to their normal position, as this maximises the 'end state comfort' of the movement (see Rosenbaum et al., 1990).

6.2.2. Method

Subjects

Thirty four subjects took part in the experiment. All were students at the University of Plymouth and were naive as to the purpose of the experiment. All subjects were right handed by self report and had normal or corrected to normal vision. Subjects were paid £3.00 or received course credit for their participation.

Apparatus and Materials

These were the same as in Experiments 3 and 4 with the following exceptions. The stimulus set consisted of coloured slides of 40 objects, twenty compatible with a clockwise wrist rotation and twenty with an anti clockwise rotation. The stimuli used are listed in Table 6.1. The objects were photographed in both upright and inverted positions but in a single orientation (as described above). Responses consisted of a small clockwise or anti-clockwise wrist rotation from the neutral starting position. Responses, and start position of the wrist, were monitored by a small device taped to the underside of the wrist of their right arm. This consisted of two pairs of mercury tilt switches connected to an Acorn Archimedes computer. One set was finely tuned about the correct start position causing a signal to be sent if the wrist orientation diverged more than + - 3 degrees from this position. The other set, used to record the response, was less finely tuned requiring a wrist rotation of > +- 9 degrees to trigger a response. Subjects sat facing the screen with the arm of their right hand resting on the arm rest. Their wrist overhung the end of the arm rest so that the response device was free to be rotated with their wrist. Subjects' wrists were aligned with the right hand edge of the screen at a distance of 30 cm.

Table 6.1. List of Objects used in Experiment 5.

Objects compatible with a clockwise wrist rotation from start position.	
Aerosol can	Lamp stand
Jug Kettle	Tall glue bottle
Wine bottle	Tea Pot
Glass coffee pot	Plastic Jug
Jug	Washing up bottle
Large Jug	Candle stick holder
Tall Milk carton	Squash bottle
Aerosol	Brown bottle
Plant sprayer	Milk jug
China Coffee pot	Watering can

Objects compatible with an anti-clockwise wrist rotation from start position.	
Radio	Hair brush
Floor brush	Large stapler
Dustpan and brush	Small stapler
Knife	Wire brush
Iron	Nail brush
Nail brush	Sieve
Teaspoon	Tea strainer
Wooden spoon	Small jar lid
Sauce pan	Small padlock
Small jar	Iron

Procedure

The experiment consisted of two blocks of 160 trials in which each object was presented twice in both upright and inverted conditions. Response mapping was blocked and pseudo-randomised so that an equal number of subjects received each mapping condition in the first block. The two response mappings consisted in making a wrist rotation clockwise if the object was upright and anti-clockwise if the object was inverted and vice versa. Subjects were instructed to respond as fast as possible whilst maintaining accuracy. Each subject received twenty practice trials per block. The position of the wrist was monitored so that trials would not proceed until the wrist was within + - 3 degrees of the correct starting position. If the wrist was outside these limits the computer emitted a rapid beeping that was terminated when the wrist was correctly aligned. A slide was projected after 2 seconds if the wrist maintained the correct starting position. The slide remained in view until a response was made or three seconds had elapsed, after which the next trial began automatically with a delay of two seconds. Thus if the wrist returned to the correct position after a trial the inter trial interval was 4 seconds. Most subjects experienced no difficulty in returning their wrist to the correct start position.

6.2.3. Results

Response Times

The average error rate for this experiment was considerably higher than the previous experiments and a 12.5% error cut off was used to avoid discarding an excessive amount of data. This resulted in the removal of six subjects from the analysis. Presumably this reflected the comparative difficulty of the wrist rotation response compared to simple key presses rather than carelessness by the subjects. Errors and responses that were more than 2 standard deviations from the mean for each subject were excluded from the analysis. For the subjects analysis, mean correct response times for each condition were subjected to a within subjects ANOVA with the independent variables Object compatibility (clockwise or anti-clockwise, response mapping (clockwise for upright objects/anti-clockwise for inverted objects (C_UP) and vice versa (AC_UP)), and response (Clockwise or Anti-clockwise). There were significant main effects of object compatibility and direction of response. Responses to objects compatible with a clockwise wrist rotation were faster (M=750.36) than to those compatible with an anti-clockwise rotation (M=817.25), [$F_{(1,27)}$ =76.15, $p < .001$]. Anti-clockwise wrist rotation responses (M=763.9) were executed faster than clockwise responses (M=803.7), [$F_{(1,27)}$=48.96, $p < .001$]. There was a significant two way interaction between response mapping and object compatibility [$F_{(1,27)}$ = 5.75, $p < .05$], (see Figure 6.1 and Table 6.2).

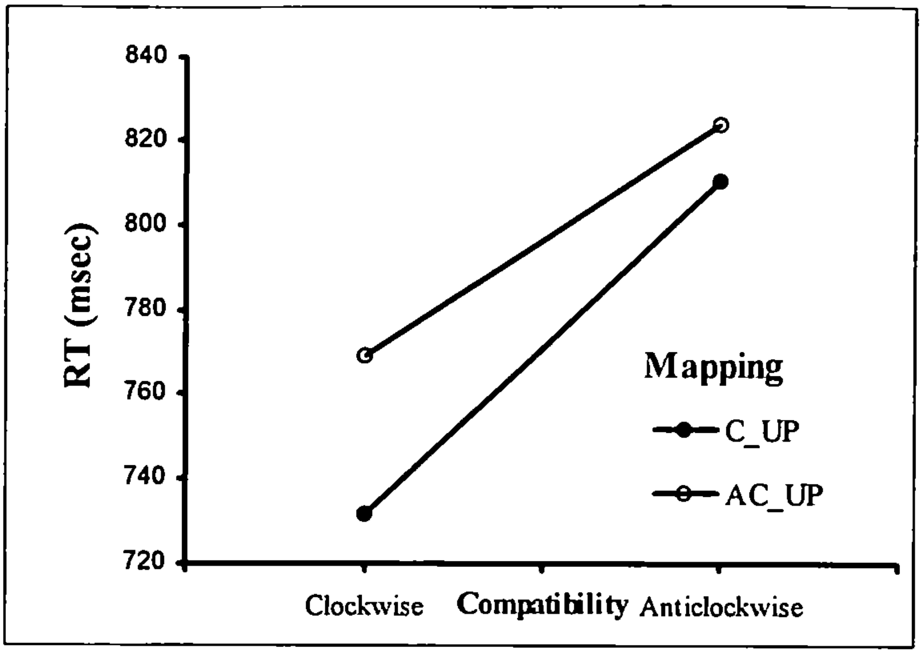
Pairwise (Newman-Keuls) comparisons of the interaction between response mapping and object compatibility showed that for objects compatible with a clockwise wrist rotation the 32 ms RT advantage for the C_UP over the AC_UP mapping was significant [$Q_{(2,56)}$=7.43, $p<.01$], whereas for the objects compatible with an anti-clockwise wrist rotation the 13 ms RT advantage for the C_UP mapping was not [$Q_{(2,56)}$=2.64, $p>.05$; $Q_{(05, 2, 50)}$=2.85]. The predicted interaction between direction of response and object compatibility was not significant [$F_{(1,27)}$=.46, p=.503].

Error rates

The pattern of error rates was similar to that of response times except for the effect of mapping (see Figure 6.1). More errors were made in C_UP mapping than in the AC_UP mapping [$F_{(1,27)}$ = 12.7, $p < .005$]. This is the opposite of the pattern found in the response time data, where the C_UP mapping was faster than the AC_UP mapping, and suggests that there could have been a trade off between speed and accuracy across mappings. However comparison of the graphs in Figure 6.1 indicates that no such trade off was occurring between mapping and object compatibility. Any trade off between mapping and object compatibility would be observable as opposing gradients between each mapping line in the RT and % errors graphs. Inspection of Figure 6.1 that the relative gradients of the lines corresponding to the two mapping conditions were preserved. The fact that they swap over indicates a possible trade off only across mappings. The only other significant effect in the errors analysis was a main effect of object compatibility, with responses to clockwise compatible objects (M=3.5) producing fewer errors than responses to anti-clockwise compatible objects (M=8.2), [$F_{(1,27)} = 45.7$, $p < .001$].

Table 6.2. Mean RTs, standard deviations and (% errors) for Experiment 5 by Object compatibility and mapping.

	Object Compatibility	
	Clockwise	Anticlockwise
C_UP	**731.7** 113.3 (4.6)	**810.6** 118.3 (11.3)
AC_UP	**769.1** 123.0 (2.4)	**823.9** 129.2 (5.1)



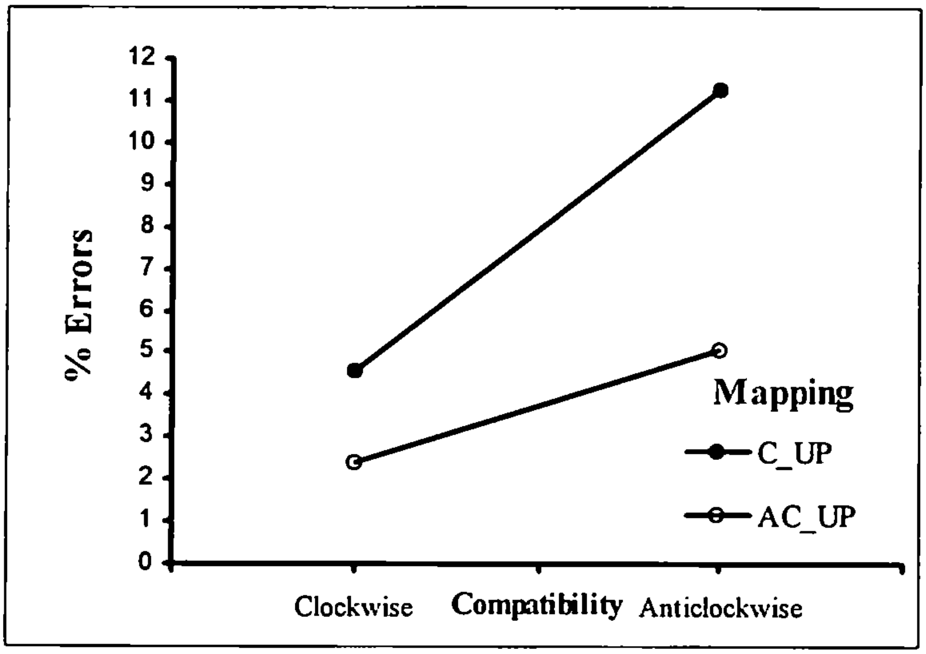


Figure 6.1. Mean RTs and % Errors for Experiment 5 by Object compatibility and Mapping. C_UP= clockwise responses for upright objects/anticlockwise responses for inverted objects. AC_UP = reverse mapping.

Materials Analysis

The response time data was analysed with objects as a random factor (nested within Object compatibility). The pattern of results was very similar to that by subjects. The main effect of Object compatibility was significant. Objects compatible with a clockwise wrist rotation were responded to faster (M=752.0) than those compatible with an anti-clockwise wrist rotation (M=826.3), [$F_{(1,38)}$ = 17.31, p < .001]. There was also a significant main effect of response mapping. Responses in the C_UP mapping (M=777.1) were faster than those in the AC_UP mapping (M=801.2), [$F_{(1,38)}$ = 16.65, p < .001]. In addition there was a significant two-way interactions between Object compatibility and mapping [$F_{(1,38)}$ = 5.91, p =.02].

For the effect of most interest, the interaction between mapping and object compatibility, Min F' was calculated and gave a non-significant result [F $min_{(1,61)}$ = 2.91, Critical value at $\alpha_{(.05)}$ =4.0].

Supplementary analyses

The subject data was also analysed using Median RT and Log RT. Both analyses gave a very similar result although for the analysis using Log RT the interaction between object compatibility and mapping only approached significance [$F_{(1,27)}$=3.77, p=.063] whereas using medians gave a significant result [$F_{(1,27)}$=4.2, p=.05].

6.2.4. Discussion

The main effect of object compatibility is readily explained by the fact that objects compatible with clockwise wrist rotations were, in most cases, larger than those compatible with anti-clockwise rotations. More importantly, perhaps, they possessed a more salient axis about which their inversion was defined, making the judgement of object inversion, and therefore which response to execute, that much easier.

The effect of response direction (anti-clockwise wrist rotations were executed on average 41 msec faster than clockwise ones) likely reflects a preference for rotating the wrist in the anti-clockwise direction. Additionally, however, it can be seen to reflect the interpretation, discussed below, of an interaction between object inversion, response and object compatibility (see Figure 6.2).

The most interesting results are the interaction between object compatibility and response mapping, and the lack of the predicted two-way interaction between response direction and object compatibility. As in the first two studies, the actual response made (clockwise or anti-clockwise wrist rotation) was determined by two factors, mapping and object inversion. An initial consideration of the lack of an interaction between the response made and object compatibility, implies that no facilitation or interference was produced by the object's grasp compatibility at the level of individual responses. There are several possible reasons for this. If response codes were automatically generated by the stimuli, and these included the parameter of wrist rotation, they may have had time to decay before the required response was retrieved[14] (see, e.g., Hommel 1994b). Reaction times in this experiment were 100 - 200 msec longer than in the previous experiments and error rates considerably higher. Thus the translation from object inversion to a direction of wrist rotation seems to have been a more difficult assignment than to a left-right push button response.

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[14] It must be pointed out, however, that there is no reason to suppose that the potentiation of the actions afforded by the object is subject to decay whilst the object *is still in view* (see the discussion of Experiments 6a and 6b for an expansion of this point).

Alternatively wrist rotation may be a component of reaching that is not planned prior to movement initiation, even in goal directed actions. Unlike grasp type, for which there is evidence of planning before movement onset (Klatzky et al., 1995), wrist rotation may only unfold as part of a synergy during an actual reaching movement. In this case, providing prior information about the direction of wrist rotation - even explicitly as part of a precue, should result in little or no facilitation. A similar point was raised by Klatzky et al., (1989) with respect to partial information about hand shape.

The interaction between the object's grasp compatibility and mapping can be described as follows. The advantage for the C_UP over the AC_UP mapping was much greater (37 msec versus 13 msec) for the clockwise compatible objects than for the anti-clockwise compatible objects (see Figure 6.1). This result might be explainable by a salient features account (Weeks & Proctor, 1990) in which the most salient (upright) stimulus was paired with a clockwise rotation. Two problems are apparent with such an explanation. First, the effect only occurred for the clockwise compatible objects. As was mentioned above, one of the reasons responses to the anti-clockwise compatible objects were longer was that this group had a less salient axis about which their inversion was defined. This lack of a salient upright-inverted dimension might, then, explain why the effect only operated for one class of objects. However, although deciding whether the anti-clockwise compatible objects were upright or inverted did take subjects longer, this should only have affected their decision time and not the relative advantage of translating the results of that decision to a response. Second, such an account would have to assume that the clockwise wrist rotation represented the most salient response. The data do not support this, as clockwise wrist rotations were significantly slower than anti-clockwise ones, and reaction time would seem to be the only available criteria for evaluating relative salience.

A closer consideration of the stimuli offers an interpretation based on the affordances of the objects in each of the two categories. It was originally presumed that both types of object afforded a grasp involving a clockwise or anti-clockwise wrist rotation regardless of whether they were upright or inverted. The orientation of the opposition axis in the object remains the same whether it is upright or inverted. However, the way we grasp an object is influenced by the actions we can perform on it. In particular, the way the hand rotates to grasp an object is sensitive to the desired final position of the object in a way that grip size, for example, is not. One of the actions that an inverted object affords is a grasp that results in returning it to its upright position. In this case an *inverted* object of the clockwise compatible type (such as an aerosol can) would require a grasp with an anti-clockwise wrist rotation. Such a grasp maximises the end-state comfort of the potential movement that results in the object being in a position for normal use (Rosenbaum et al., 1990). If this were the case the C_UP mapping would maintain compatibility when the object was upright and inverted (as clockwise responses were required for upright objects and anti-clockwise for inverted objects under this mapping rule). In contrast, with the anti-clockwise compatible objects no such effect of mapping would be expected. This is because these objects still require the same grasp type, and direction of wrist rotation, regardless of whether they must be returned to upright (for example a stapler lying on its back positioned at right angles to the line of sight). In all cases they must be grasped from above with the thumb and fingers (of the right hand) turning anti-clockwise to align themselves along the opposition axis. If the object is to be returned to upright this must be achieved by subsequent manipulations after the initial grasp has been performed. This account would, therefore, predict that anti-clockwise responses should always be faster to the anti-clockwise compatible objects, regardless of inversion, whereas anti-clockwise responses should only be faster for inverted objects in the clockwise compatible category.

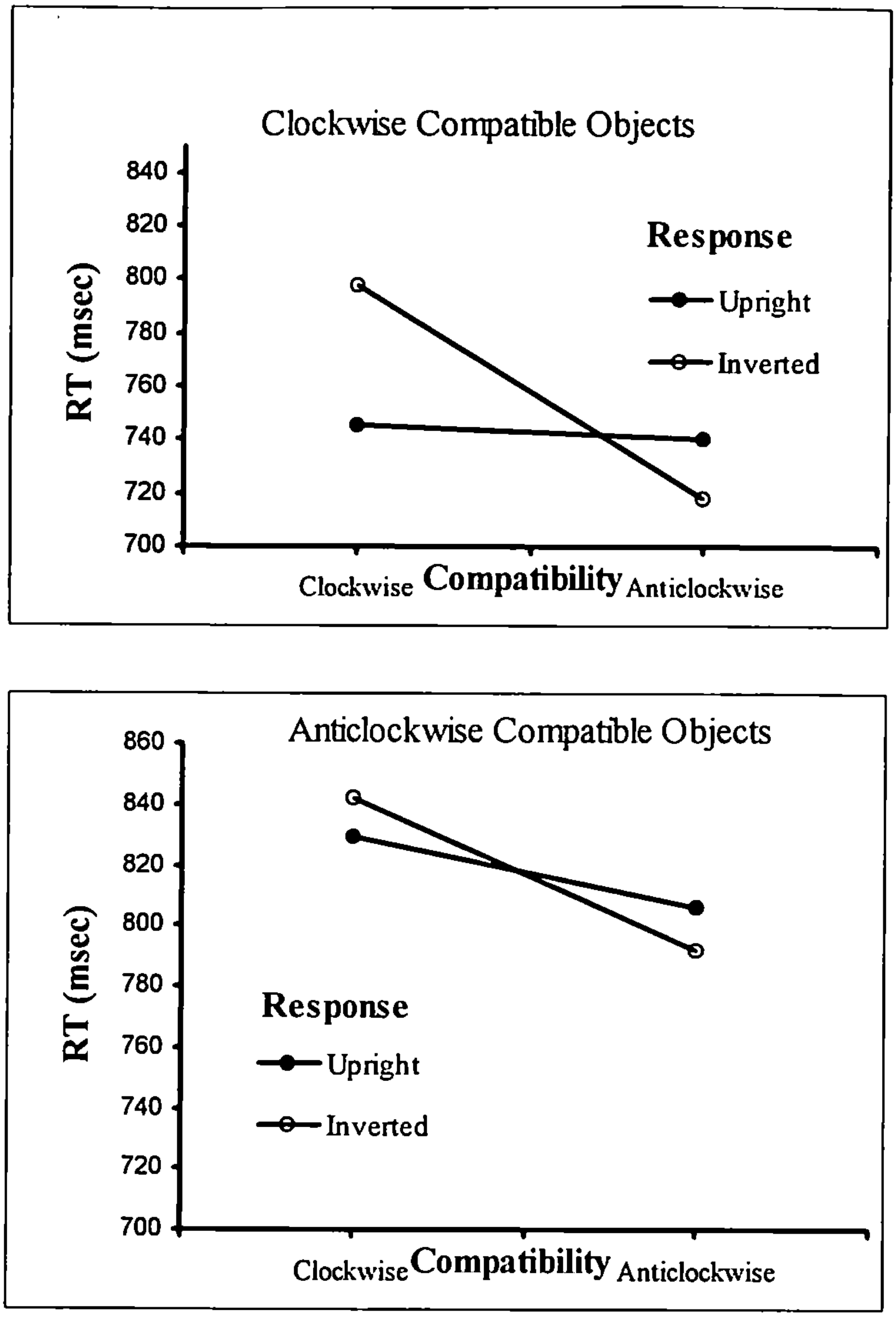

Figure 6.2. Mean RTs for Experiment 5 as a function of Object Compatibility, Inversion and Response.

An examination of the data broken down by the responses executed to each object type and at each inversion gives some support to this explanation of the significant two way interaction (see Figure 6.2). For the clockwise compatible objects, clockwise wrist rotations were executed faster to upright objects than to inverted ones, whereas anti-clockwise rotations were executed faster to inverted objects than to upright objects. In contrast, for the anti-clockwise compatible objects, the difference between responses to upright and inverted objects was minimal. On average, anti-clockwise rotations were executed faster than clockwise ones, with only a very slight advantage for clockwise rotations to upright objects and anti-clockwise rotations to inverted objects (see Table 6.3).

Table 6.3. Means and standard deviations for Experiment 5 by object compatibility, response and inversion.

	Clockwise compatible		**Anticlockwise compatible**	
Response	Upright	Inverted	Upright	Inverted
Clockwise	**745.67**	**798.07**	**829.36**	**841.7**
	122.76	127.7	131.09	139.03
Anti-clockwise	**740.05**	**717.63**	**806.06**	**791.86**
	113.06	103.22	118.3	102.97

Because of the potential importance of object inversion on the affordances generated by the objects a further analysis using inversion as a factor was carried out. It is important to point out that in this, and any other SRC study in which a stimulus property is used to cue a response under a mapping rule, one of the three factors: mapping rule, stimulus property and response is always redundant, as it can be derived from the other two. The analysis using object inversion and response as factors together with object compatibility is exactly equivalent to that using mapping and response. Thus the interaction between object compatibility and mapping corresponds to a three-way interaction between object inversion, response and object compatibility. Separate analyses of this interaction broken down by object type helps to clarify the data presented in Figure 6.2. For the clockwise compatible objects the interaction between response and inversion was significant [$F_{(1,27)}$ =4.98, p=.034] whereas for the anti-clockwise objects it was not [$F_{(1,27)}$ =.80, p=.37], a result that lends support to the interpretation given above of the differential effect of object inversion on the affordances of the two types of objects. Post hoc comparisons using the Newman-Keuls procedure found the difference for the clockwise objects to be significant for clockwise responses [$Q_{(2,27)}$=6.22, p<.01] but only approached significance for the anti-clockwise responses [$Q_{(2,27)}$=2.66, p>.05]. For the anti-clockwise objects neither comparison was significant [$Q_{(2,27)}$=1.5, p>.05] clockwise responses; [$Q_{(2,27)}$=1.7, p>.05] anti-clockwise responses); [$Q_{(.05,2,27)}$=2.91, MSe= 1419].

This analysis therefore, suggests caution in interpreting the insignificant response by object compatibility effect as evidence against the existence of a Simon effect from the objects' affordances. However a full understanding of the effect would have to involve further experimentation in which the effects of mapping and object inversion were not confounded. The data nonetheless provide preliminary evidence for the existence of compatibility relations between an object's affordance for grasping and responses that share a component of that action other than hand choice.

The purpose of the next experiments was to examine the compatibility effect of clockwise/anticlockwise objects without using inversion as the response cue, thereby ensuring that the clockwise compatible objects were always only compatible with clockwise responses. If object inversion was responsible for the effect observed in Experiment 5 then keeping the objects in their upright orientations should result in a straightforward compatibility effect of object type on rotation responses.

6.3. Experiment 6a : Wrist rotation responses to real objects cued by tone.

6.3.1. Introduction

In Experiment 6a wrist rotation responses were examined under reaction time conditions in the presence of objects compatible with either clockwise or anticlockwise wrist rotations. To avoid the confounding of the object's compatibility with the stimulus property used to cue responses, inversion was not used as the response relevant stimulus dimension. Instead the objects were always viewed in the upright position. Under these conditions tall cylindrical objects were always only compatible with a clockwise wrist rotation if they were to be grasped. Responses were cued by a high or low pitched tone as in Experiment 1. It was decided to use a tone cue for response determination because of the difficulty in finding a stimulus property, other than inversion, that requires enough visual processing to ensure that the structural characteristics of the objects that determine its affordances are fully processed when the response is selected. Object colour, for example, could be extracted with only a very limited amount of focused attention to the objects' shape. In order that subjects did, in fact, attend to the objects the experiment was set up under the guise of a dual task involving reaction times to tones and recognition memory for objects. As in Experiments 1 and 2 real objects were used as stimuli.

6.3.2. Method

Subjects

32 subjects took part in the experiment. All were right handed by self report and had normal or corrected to normal vision. They were all students at the University of Plymouth and received course credit or a £2.00 cash payment for their participation.

Apparatus and Materials

The stimuli consisted of forty objects, twenty tall cylindrical objects compatible with a clockwise wrist rotation and twenty either of small size or possessing horizontal grasp axes that were compatible with an anti-clockwise wrist rotation. The list of objects used is given in Table 6.4. The wrist rotation responses were measured by a modified version of the device used in the previous experiments and required slightly smaller rotational movements to trigger either a clockwise or anti-clockwise response (+ - 3 degrees for the start position and + - 6 degrees for the response). The stimuli were presented approximately 20 cm in front of the subjects finger tips inside the one-way glass apparatus described in Experiment 1. Subjects sat with the base of their right forearms resting on a cylindrical arm rest that gave support whilst allowing the wrist freedom of rotational movement. Their arms were angled so that the hand was pointing toward the centre of the stimulus box. Because a tone was used to cue responses, the rapid beeping used to give feedback about the initial position of the wrist in Experiment 5 was not used. Instead, feedback about the start position of the wrist was given visually by small red- light suspended above the glass screen that could be seen as a reflection at, approximately, the position on the glass under which the objects would appear. If subjects' wrists were outside the starting limits the red light would flash on and off rapidly. As the wrist approached the correct position the flashing would become less rapid and finally stop, with the light on continuously, when the correct start position was achieved.

Table 6.4. List of objects used in Experiment 6a.

Objects Compatible with a clockwise wrist rotation

Brown Bottle	Washing up Bottle	Upright Wood Block
Lemonade Bottle	Aerosol	Glass Jar
Wine Bottle	China Bottle	Plastic Tube
Squash Bottle	Bleach Bottle	Cardboard Tube
Cardboard Tube	Cardboard Tube	Upright Cardboard Tube
Plastic Bottle	Aerosol	Tall Jar
Oil Bottle	Glass Coffee Pot	

Objects compatible with an anticlockwise wrist rotation

Small sponge	Garden fork	Pen
Match box	Paint brush	Tooth Brush
Match box	Screw driver	Screw driver
Cardboard box	Scissors	Horizontal block
Cardboard box	Pen	Pen
Stapler	Spoon	Plastic Box
Table fork	Biro	

Procedure

Subjects were told that the experiment involved two tasks - a choice reaction time task and a recognition memory task. At the beginning of each trial subjects had to ensure that their wrist was in the correct orientation by attending to the light reflected on the glass screen. When their wrist remained in the correct starting position for 1 second, during which time the red light would remain on without flashing, the red light was turned off and the light inside the stimulus box came on after an interval of 400 msec. The termination of the red monitoring light served as a warning cue. The object remained illuminated for 700 msec. Subjects were instructed to pay close attention to each object but not to rehearse previous ones. It was explained that the memory task which was to take place halfway through the experiment and at the end was of recognition and not recall, and that simply making sure they viewed each object whilst the light was on was sufficient. Immediately after the light went off a high or low pitched tone sounded and subjects had to make either a clockwise or anticlockwise wrist rotation response depending on the mapping rule given to them at the start of the experiment. They were instructed to respond as fast as possible whilst remaining accurate. Incorrect responses were immediately followed by a 800 msec bleep from the computer that was approximately halfway in pitch between the two tones used to cue the responses. Correct responses were also followed by a short tone (100 msec), as there was no other way of letting subjects know that they had actually made the required response. Each of the forty objects were presented, in randomised order, twice in both halves of the experiment. After the first eighty trials the recognition test was carried out. Subjects were told that an object would be exposed for a brief (20 msec) duration in the same location as before and they had then to say whether or not they recognised it. Twelve recognition trials were given in which half of the objects had been previously viewed by the subjects and half had not. These were picked at random by the experimenter. The recognition task was repeated at the end of the experiment using a different subset of stimulus objects. The experiment thus consisted of 160 choice reaction time trials and twenty four recognition trials. At the beginning of the experimental session subjects were first allowed to hear examples of each tone and then given practice trials making choice responses to the tones depending on the mapping rule assigned to them. This also served as practice for monitoring their wrist start position using the red warning light. After fifteen such trials they were given further trials until they made ten consecutive correct responses. This practice procedure was then followed by ten practice trials of the actual task. The trials proceeded automatically with a response execution to wrist monitoring interval of 5 seconds during which time the experimenter placed the next object in the stimulus box. As in Experiment 2 the objects to be placed in the box on each trial were displayed to the experimenter on the screen of an Acorn Archimedes computer out of sight from the subject. Each subject used only one mapping rule for the entire experiment (either high pitch - clockwise responses / low pitch anticlockwise responses or the reverse). Subjects were also told that they could, at any time, halt the progression of the experimental trials by deliberately keeping their wrist in an incorrect starting orientation until they were ready to continue.

6.3.3. Results

Response times

The data from four subjects was not analysed as their error rates exceeded 12.5%. One subject was also removed from the analyses as they failed to recognise more than 2 out of the 12 seen objects in the recognition task even when these were presented for a much longer (100 msec) duration at the end of the experiment. For the rest the condition means were obtained after removing reaction times more than two standard deviations above or below each subject's overall mean. These were analysed in a partially within subjects ANOVA with within subjects factors of Object Compatibility (Clockwise or Anti-clockwise) and Response (Clockwise or Anti-clockwise) and the between subjects factor of Mapping rule (High pitch - clockwise responses / Low pitch - Anti-clockwise responses (H_C) or the reverse (L_C)). This analysis revealed a main effect of mapping with responses in the H_C mapping (M=390.6) producing faster reaction times than in the L_C mapping (M=450.1), [$F_{(1,26)}$=4.39, p=.046]. The predicted interaction between object compatibility and response failed to reach significance [$F_{(1,26)}$=1.26, p=.272]. The relevant data are presented in Figure 6.3 for ease of comparison with Experiment 6b. Post hoc comparisons confirmed that the compatibility effect observable in Figure 6.3 for clockwise responses was not significant [$Q_{(4,26)}$=2.17, p>.05; $Q_{(.05,4,26)}$=3.87, Mse=327.9]. There was, however a significant three-way interaction between Object compatibility, Response and Mapping, displayed in Figure 6.4 [$F_{(1,26)}$=4.24, p=.050].

Separate analyses of the data broken down by mapping[15] revealed that the interaction between Object compatibility and response was not significant in either mapping condition although it approached significance in the L_C mapping (the lower graph in Figure 6.4). For the H_C mapping [$F_{(1,26)}$=0.76, p=.399] whereas for the L_C mapping [$F_{(1,26)}$=3.55, p=.082]. Summary data are given in Table 6.5.

Error rates

Analysis of the error data revealed a single significant interaction between Object compatibility and Mapping. In the H_C mapping more errors were made to objects compatible with a clockwise wrist rotation (M=7.1) than to those compatible with an anti-clockwise rotation (M=5.8) whereas in the L_C mapping errors were more numerous to anti-clockwise compatible objects (M=5.7) than to clockwise compatible objects (M=4.6), [$F_{(1,26)}$=4.31, p=.048]. The three way interaction between Object compatibility, Response and Mapping approached significance [$F_{(1,26)}$=4.18, p=.051] and is displayed in Figure 6.5.

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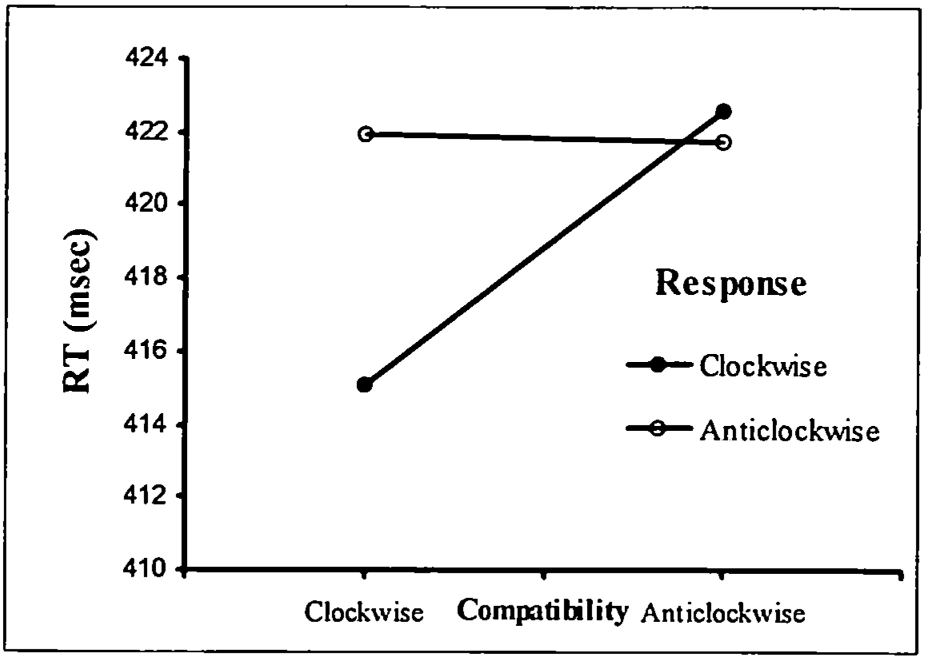
[15] Examining the simple interaction effects across the two mappings is, of course, not the only way to understand the three-way interaction. However in this instance it provides the greatest contrast. Breaking the data down across object compatibility or response did not reveal significant interactions at one level and not at the other in either case.



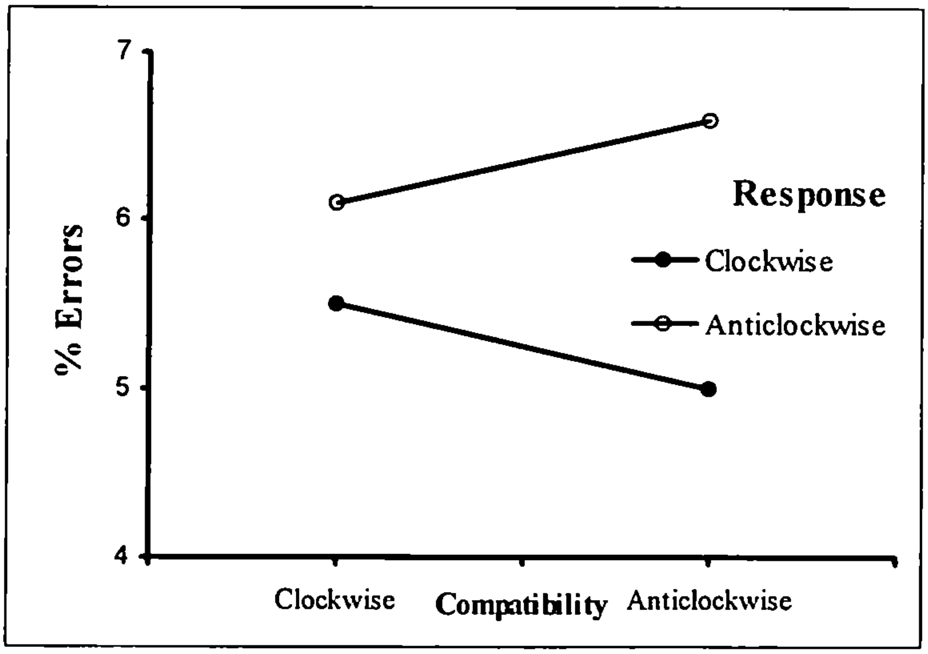


Figure 6.3. Mean RTs and % errors for Experiment 6a by response and object compatibility.

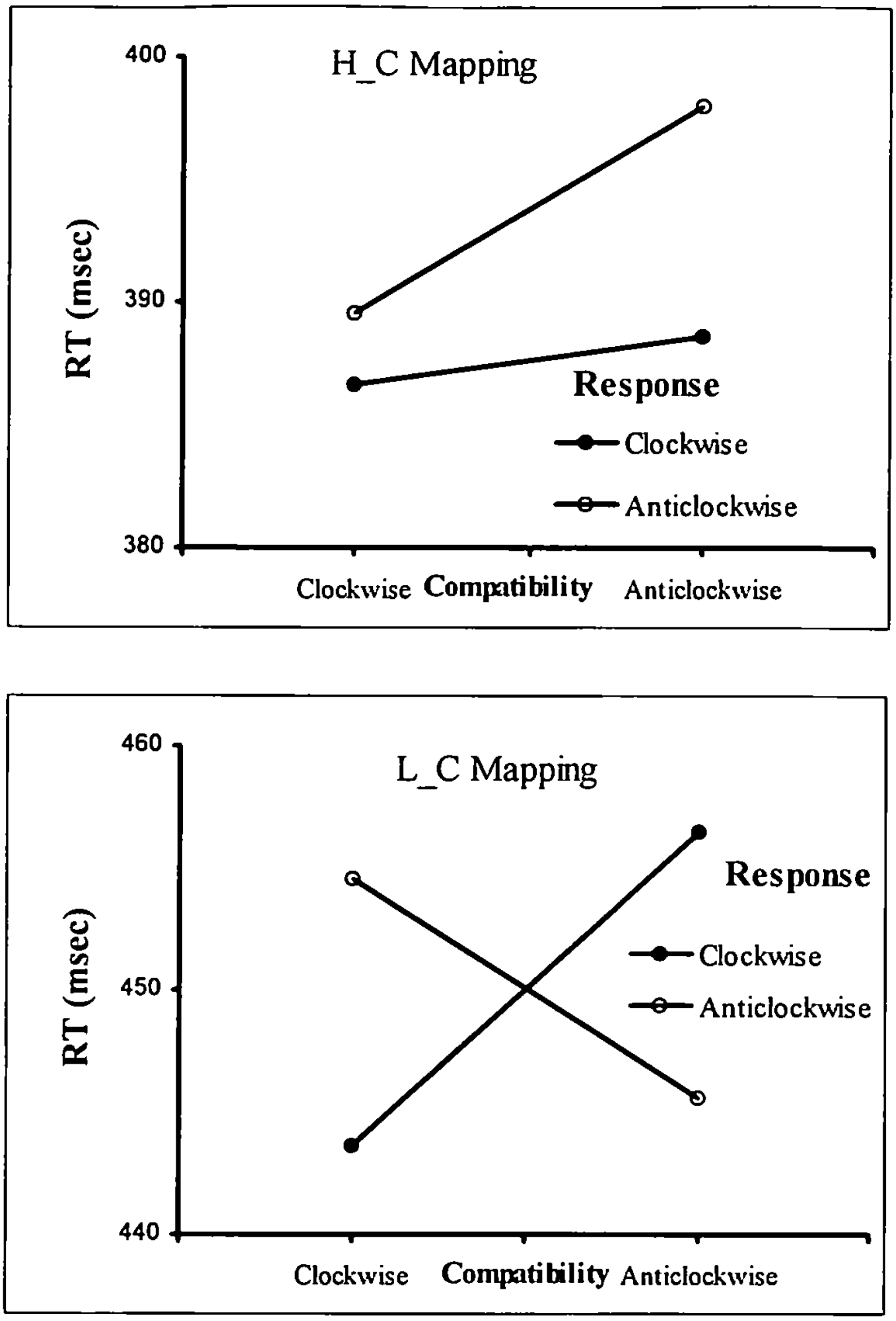
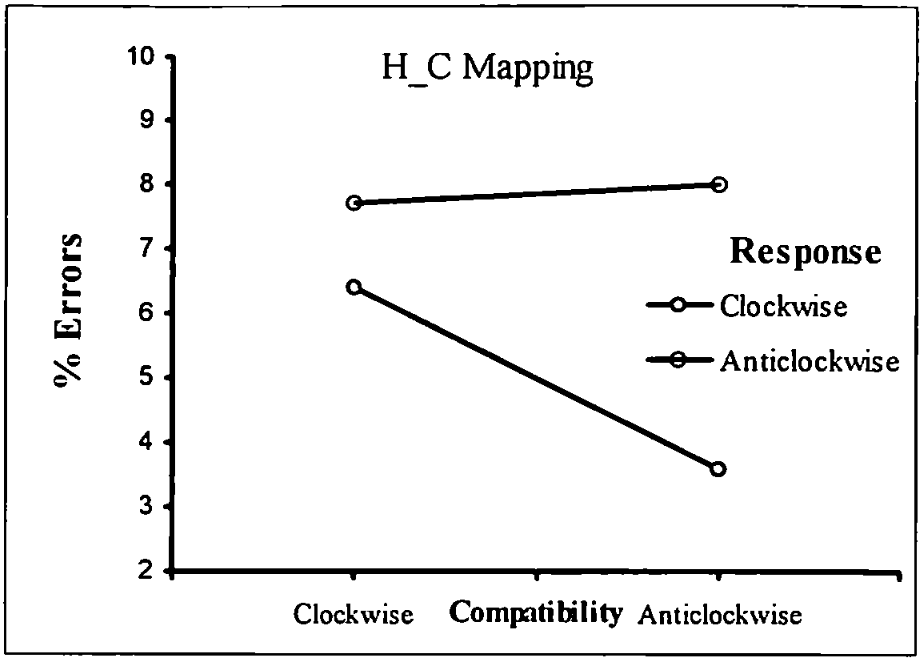


Figure 6.4. Mean RTs for Experiment 6a by Response, Object compatibility and Mapping.

Table 6.5. Mean RT, standard deviations and (% errors) for Experiment 6a by Object Compatibility, Response and Mapping.

	Clockwise Compatible		**Anti-clockwise Compatible**	
Mapping	**Clockwise responses**	**Anticlockwise responses**	**Clockwise responses**	**Anticlockwise responses**
H_C	**386.6** 73.7 (6.4)	**389.5** 63.8 (7.7)	**388.6** 64.0 (3.6)	**397.9** 66.3 (8.0)
L_C	**443.6** 94.7 (4.6)	**454.5** 73.7 (4.6)	**456.5** 91.1 (6.4)	**445.6** 87.8 (5.0)



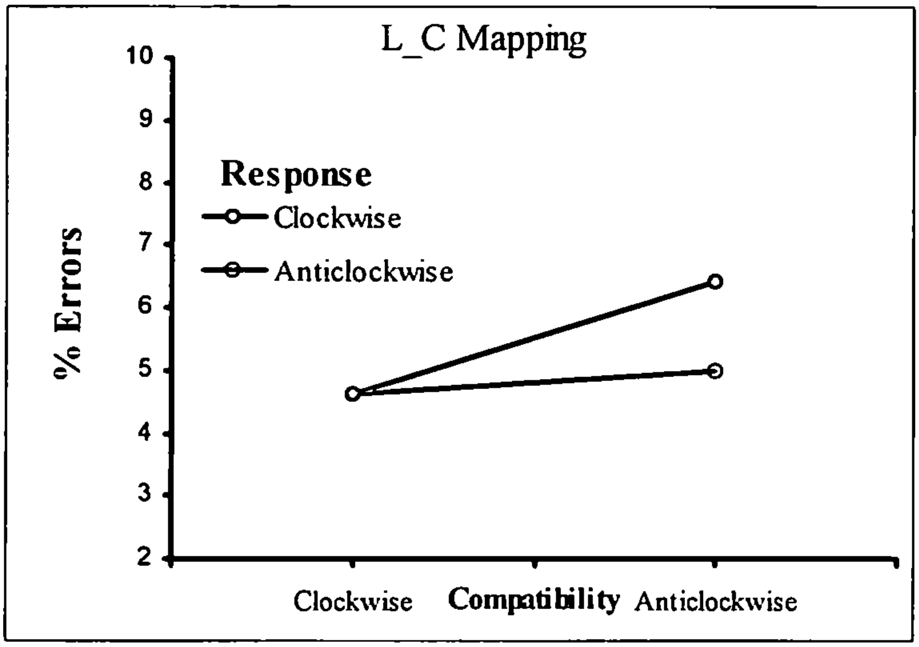


Figure 6.5. Percentage error rates for Experiment 6a by Object Compatibility, Response and Mapping.

Materials Analysis

Analysis of the response time data with Objects as a random factor (nested within Object Compatibility) showed a similar pattern of results to that in the analysis by subjects. The effect of mapping was highly significant with responses in the H_C mapping (M=391.3) being faster than those in the L_C mapping (M=450.2), ($F_{(1,38)}$=371.3, p<.0001). In addition the three-way interaction between Object compatibility, Response and Mapping was significant and of identical form to that observed in the subject analysis ($F_{(1,38)}$=6.08, p=.018).

Supplementary Analyses

Analysis of the subject data using Median RT and Log RT revealed similar but not identical results to the analysis using 2sd cut-offs. As observed in the latter, both analyses failed to show any evidence of the predicted compatibility effect between Response and Object Compatibility [$F_{(1,26)}$=.08, p=.785, Median RT]; [$F_{(1,26)}$=.02, p=.903, Log RT]. The main effect of Mapping only approached significance in both analyses [$F_{(1,26)}$=3.34, p=.079, Median RT]; [$F_{(1,26)}$=3.92, p=.058, Log RT]. Using Log RT the three way interaction between Object Compatibility, Response and Mapping approached significance [$F_{(1,26)}$=3.94, p=.058]. With Median RT, however it did not [$F_{(1,26)}$=1.61, p=.216].

6.3.4. Discussion

The most important result of Experiment 6a was the absence of the predicted compatibility effect between clockwise / anti-clockwise responses and clockwise or anti-clockwise compatible objects. There is however, some evidence that there was such a compatibility effect within the L_C mapping although the result must be treated with some caution given the results of the analysis using Median RT. The main effect of mapping could be explained by the salient features model of SRC on the assumption that the High pitched tone and the clockwise response represent the most salient features of the stimulus and response sets and the low tone and anticlockwise response the least salient. The results of Experiment 5, however, do not provide any evidence for assuming that clockwise wrist rotations represent the most salient response. Either way the effect of mapping is only of minor interest. It is to be expected that in many cases one mapping may well be easier to implement than another. Indeed this is to be expected, according to Kornblum et al's (1994) account whenever there is Dimensional Overlap between the relevant stimulus and response properties. As mentioned in Chapter 3 the difficulty with this is the circularity in the assertion of DO from the existence of a mapping effect.

The average reaction times in this experiment were quite fast compared to Experiment 5. This likely reflects the nature of the dual task involved. When subjects actually made their responses they were simply performing a choice reaction time task to a tone stimulus. In contrast to all the previous experiments (including Experiment 1[16]) subjects did not have to determine the correct response by extracting visual information from across the varying stimulus set. It was assumed that any potentiation of the actions afforded by the object

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[16] Although in Experiment 1 responses were cued by tone stimuli the actual reaching response still had to be prepared based on the structural properties of the objects. They were not there simply reaching forward with either the left or right hands but had to interact with the objects.

would still be active for a short period after the object's exposure and thus be capable of facilitating or interfering with the required responses. The significant three-way interaction suggests that any compatibility effect tended to be stronger in the more difficult of the two mappings (as measured by response times), although within neither mapping did it reach significance. If the differences in the compatibility effect within the two mappings was due to the decay of any automatically activated action components one would expect the reverse pattern. At least with regard to automatically activated spatial codes the evidence from SRC studies implies that they exert compatibility effects only when response selection takes place shortly after stimulus onset (Hommel 1994a, 1994b). The longer the delay between stimulus onset and response selection the less the effect of automatically activated codes. This, of course, assumes that the activation of action components follows a similar time course to those of purely spatial codes, an assumption which has no empirical support one way or the other at present - the primary aim of this program being to establish their existence. Two related factors may have been more influential in the pattern of results observed. The responses were executed when the stimulus objects were not illuminated. When the response was actually selected subjects were merely performing a straight forward choice reaction time task. Under these conditions the difference in the ease of implementing the two mapping rules may have been critical. Under the highly compatible H_C mapping rule response selection may have been little influenced by any partially activated action codes - its ease of implementation may have been sufficient to override any competing codes. Such an effect would likely be exaggerated when response selection was being determined via a different modality to that generating any competing response codes.

The execution of responses after object illumination may have been critical for other, potentially more important reasons. As pointed out in Chapter 2 the representation of action components during goal directed acts involves processing in the dorsal visual stream.

The visuo-motor representations involved are highly transient and rapidly updated reflecting the need to continuously monitor the precise position and orientation of the goal object and the state of the motor system (Goodale, 1993, Goodale & Servos, 1992). The offset of object illumination might thus be expected to rapidly result in the termination of action components generated by the objects. Such a process would act over and above the decay of any automatically activated components on account of their irrelevance to the task. It remains a matter for empirical investigation whether activated components of action are subject to decay under conditions in which actual actions are not required. They may, for instance, be rapidly formed but equally rapidly decayed as the explicit, intentional, task requirements take over the action system. Such a process would take place even whilst the objects remained in view. This a very different process to that of replacement, however, where new visual input results in the rapid updating of the visuomotor system. It would be important therefore to examine the effect under conditions where the response was executed whilst the object was still in view This was carried out in Experiment 6b.

6.4. Experiment 6b: Wrist rotation responses to real objects cued by tone during object exposure.

6.4.1. Introduction

For reasons outlined above it was decided to repeat Experiment 6a under conditions in which the tone used to cue clockwise or anti-clockwise wrist rotation responses was presented whilst the stimulus object remained in view.

6.4.2. Method

Subjects

All subjects used were right handed by self report and had normal or corrected to normal vision. None of them had taken part in the previous experiment. In order that this experiment could be compared to Experiment 6a subjects were run until there were 14 in each mapping condition who satisfied the error criteria. This required a total of 32 subjects -four having to be replaced for exceeding the error criteria. All were students at the University of Plymouth and received course credit or £2.00 for participating.

Apparatus and Materials

These were identical to those of Experiment 6a.

Procedure

The procedure was identical to that of Experiment 6a except for two changes. The tone stimulus used to cue the responses was given after the object had been illuminated for 700 msec +-a random window of 50 msec. The use of a random time window was to try and prevent subjects adopting a strategy of preparing for the onset of the tone and decreasing their attention to the object at that point. After the tone cue was given the light remained on until a response was executed or three seconds had elapsed. Because the offset of the illuminating light served as feedback that a response had been carried out no tone followed correct responses.

6.4.3. Results

Response times

Subjects were run until data from 14 in each mapping condition had been collected that fulfilled the 12.5% error rate criteria. The method of analysis was the same as that used in Experiment 6a. The analysis of variance on subjects' trimmed condition means showed a main effect of object compatibility not present in Experiment 6a but present in Experiment 5. Responses executed in the presence of objects compatible with a clockwise wrist rotation during grasping produced faster reaction times (M=357.6) than those compatible with an anti-clockwise rotation (M=363.9), [$F_{(1,26)}$=5.61, p=.026].

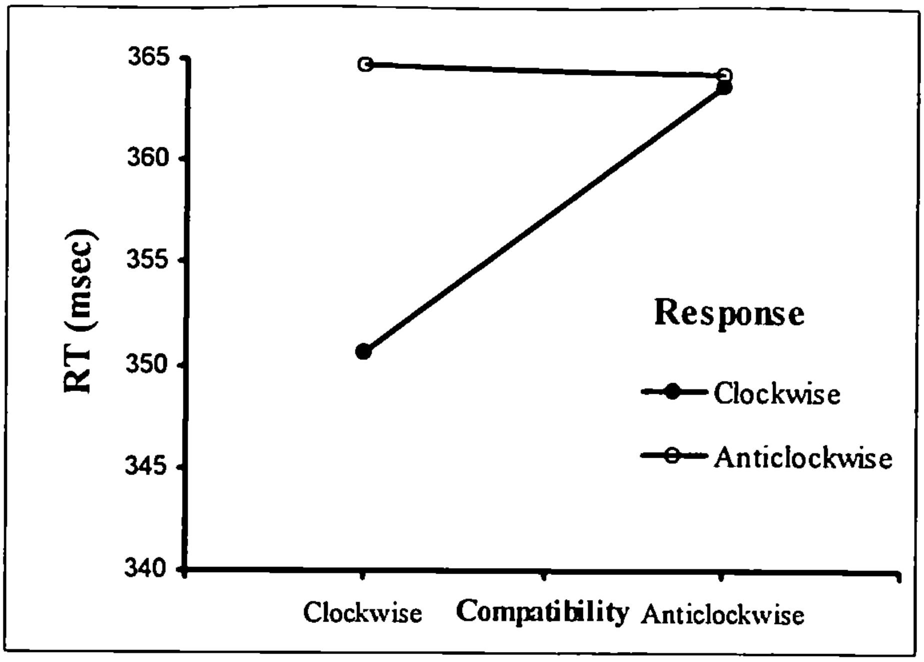
In marked contrast to Experiment 6a the effect of mapping was not significant both the H_C and L_C mapping having identical means of 360.8 msec (p=.999). The three-way interaction between Response, object compatibility and mapping was also not significant in contrast to Experiment 6a [$F_{(1,26)}$=1.10, p=.304]. The most important result, however, was that the interaction between object compatibility and response was significant when responses were executed with the object still in view. In the presence of clockwise compatible objects clockwise responses (M=350.6) were executed faster than anti-clockwise responses (M=364.6) whereas in the presence of anti-clockwise compatible objects the clockwise responses (M=363.62) and anti-clockwise responses (M=364.19) hardly differed [$F_{(1,26)}$=9.37, p=.005]. This interaction is displayed in Figure 6.6 and Table 6.6. Pairwise comparisons (Newman-Keuls) showed that the difference between clockwise and anti-clockwise responses was only significant for responses in the presence of clockwise compatible objects [$Q_{(4,26)}$=6.37, p<.01; $Q_{(.01,4,26)}$=4.85; MSe=135.4].

Error rates

The pattern of errors was similar to those of response times see Figure 6.6. Analysis of subjects error rates showed a single significant effect of the interaction between object compatibility and mapping. In the presence of clockwise compatible objects more errors were made in the L_C mapping (M=7.1) than in the H_C mapping (M=5.3) whereas in the presence of objects compatible with an anti-clockwise wrist rotation marginally more errors were made in the H_C mapping (M=7.0) than in the L_C mapping (M=6.8), [$F_{(1,26)}$=4.38, p=.046].

Table 6.6. Mean reaction times, standard deviations and (% errors) for Experiment 6b by response and object compatibility.

	Response	
Compatibility	Clockwise	Anti-clockwise
Clockwise	**350.6** 83.8 (5.9)	**364.6** 91.4 (6.5)
Anti-clockwise	**363.6** 81.3 (7.3)	**364.2** 91.6 (6.4)



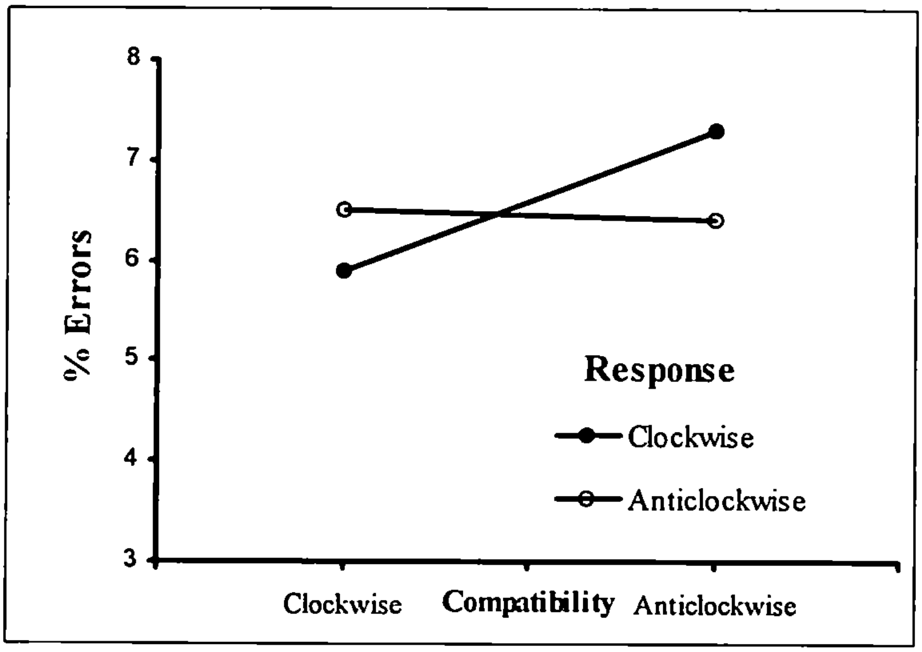


Figure 6.6. Mean reaction times and percentage errors for Experiment 6b by response and object compatibility.

Materials analysis

An analysis of the data with objects as a random factor revealed a main effect of Response which was not significant in the analysis by subjects. Clockwise wrist rotations (M=359.6) were executed faster than anti-clockwise wrist rotations (M=365.0) [$F_{(1,38)}$=4.58, p=.039]. The effect of object compatibility observed in the subjects analysis was not significant [$F_{(1,38)}$=1.97, p=.169]. The effect of interest between Object compatibility and response only approached significance in the materials analysis [$F_{(1,38)}$=3.66, p=.063]. In addition there was a significant two-way interaction between response and mapping which is most plausibly explained as an effect of the saliency of the two tones. Clockwise responses in the H_C mapping, and therefore to the high pitched tone, (M=354.5) were executed on average 8.6 msec faster than in the L_C mapping to the low tone (M=363.15) whilst anti-clockwise responses were executed on average 10 msec faster in the L_C mapping to the high tone (M=360.8) than in the H_C mapping (M= 370.7) to the low tone cue [$F_{(1,38)}$=8.45, p=.006].

Supplementary analyses

Analyses using Median and Log RT confirmed the significance of the Object compatibility by Response interaction. Using Median RT [$F_{(1,26)}$=11.95, p=.002]; using Log RT [$F_{(1,26)}$=4.91, p=.036]. No other effects were significant for the analysis using Log RT. Medians, however, gave a significant result for the effect of Object Compatibility, with the clockwise compatible objects producing faster (M=348.5) median RTs than the anti-clockwise compatible objects (M=358.8), [$F_{(1,26)}$=7.7, p=.010], a result also found in the analysis using 2 standard deviation cut-offs. The medians analysis also gave a significant three-way interaction between response, object compatibility and mapping [$F_{(1,26)}$=8.59, p=.007], which had a very similar form to that observed in Experiment 6a, see Figure 6.7 (the pattern of means shown here is identical to those computed using the 2sd cut off).

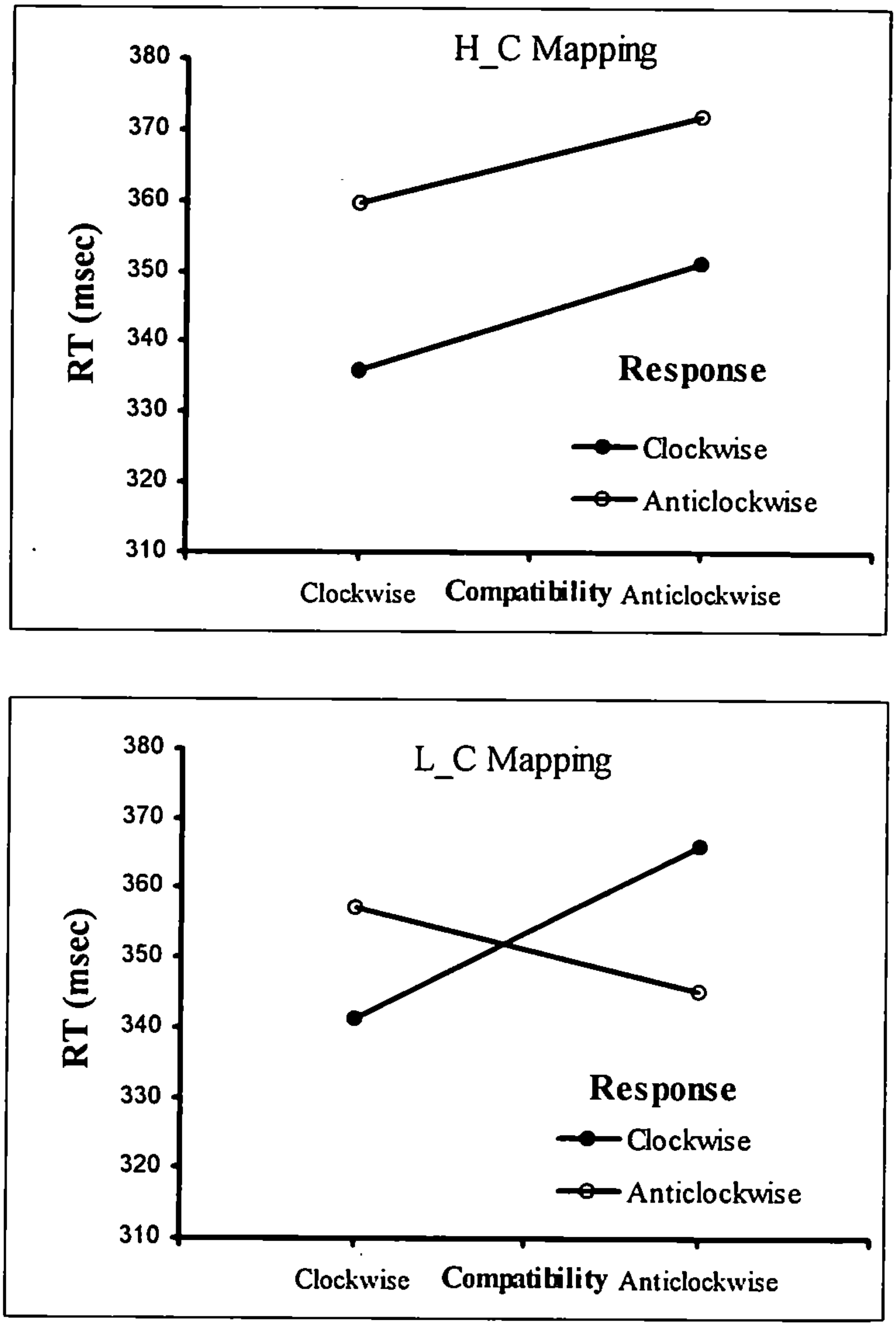


Figure 6.7. Mean median RTs for Experiment 6b by Response, Object Compatibility and Mapping.

Comparison of Experiments 6a and 6b.

In order to draw a statistical comparison between the two conditions in which the responses were executed an ANOVA on the pooled data from both experiments was carried out. This analysis showed no evidence for a difference in the response by object compatibility effect across experiments. The three-way interaction that would indicate this did not approach significance [$F_{(1,52)}$=0.5, p=.48]. Rather the pooled data showed a significant two-way interaction between response and object type displayed in Figure 6.8. Over both experiments clockwise responses to clockwise compatible objects (M=382.9) were faster than to anti-clockwise compatible objects (M=393.1) whilst there was almost no difference in anticlockwise responses to objects of either type (M=393.3 and 393.0), [$F_{(1,52)}$=6.75, p=.012]. A follow up comparison using Newman-Keuls confirmed that the difference between clockwise responses to clockwise and anti-clockwise compatible objects was significant [$Q_{(3,52)}$= 5.0, p<.01, $Q_{(.01,3,52)}$ = 4.41; Mse=232].

The overall ANOVA also showed a main effect of object compatibility with responses to clockwise compatible objects being faster than anti-clockwise ones [$F_{(1,52)}$=4.02, p=.05], although this result is largely a consequence of the pattern of two-way interaction. The main effect of experiment was significant with response times on average 60 msec faster in Experiment 6b (M=360.8) than 6a (M=420.3), [$F_{(1,52)}$=7.56, p=.008]. The only other significant effect was the three-way interaction between object compatibility, response and mapping displayed in Figure 6.9, [$F_{(1,52)}$=5.28, p=.026].

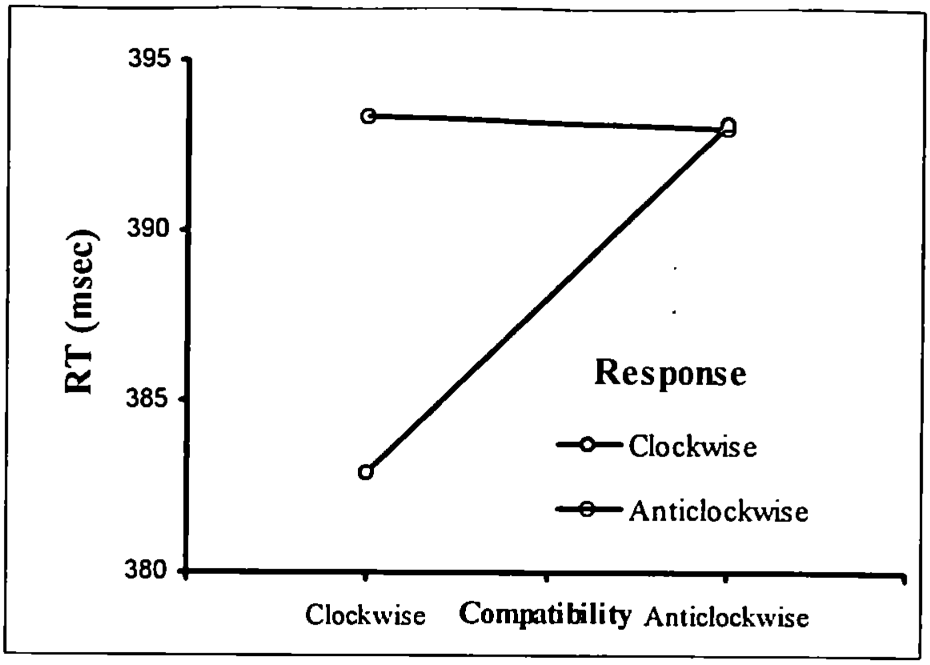
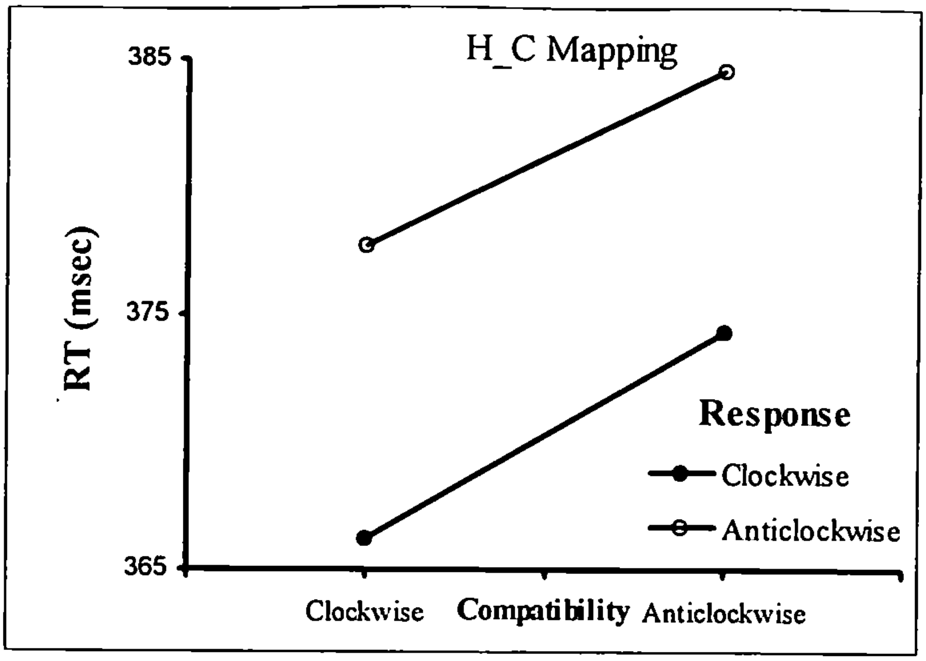


Figure 6.8. Response by Object compatibility interaction for the data from both Experiments 6a & 6b.

Analysis of materials showed a similar pattern of results as that by subjects. The response by object compatibility interaction was significant [$F_{(1,38)}$=6.99, p=.012] as was the three-way interaction between this and mapping [$F_{(1,38)}$=6.74, p=.013]. In contrast to the result across subjects the main effect of object compatibility was not significant, whilst that of response was [$F_{(1,38)}$=4.71, p=.036], indicating a slight RT advantage for clockwise responses (M=394.8) over anticlockwise ones (M=399.2).



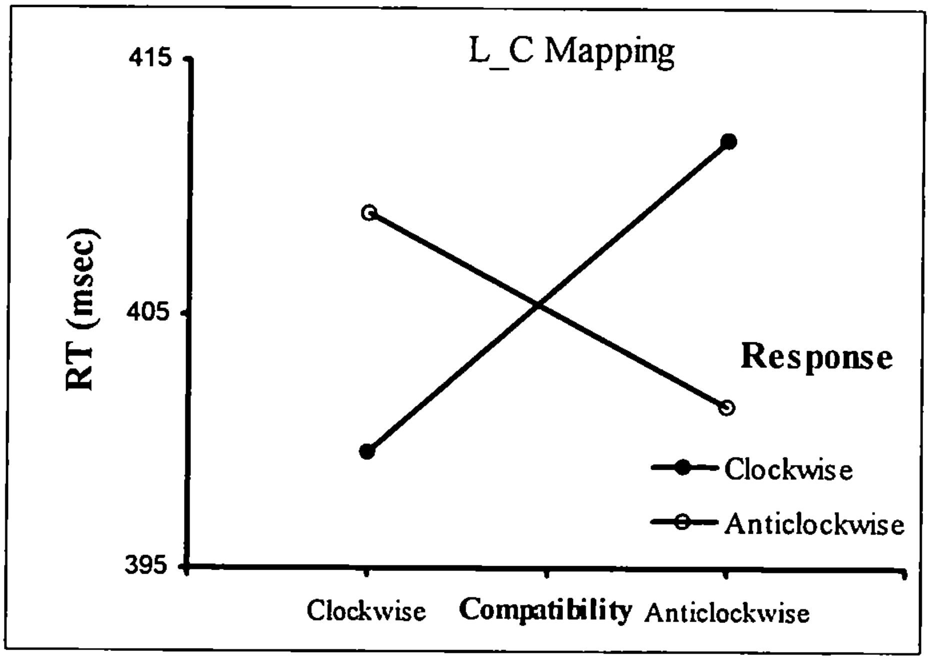


Figure 6.9. Object compatibility by Response by Mapping interaction for the pooled data from Experiments 6a & 6b.

As in the subjects analysis the main effect of experiment was highly significant [$F_{(1,38)}$=314.41, p<.0001]. The materials analysis also revealed a highly significant effect of mapping [$F_{(1,38)}$=218.8, p<.0001] that needs to be interpreted with reference to a similarly significant interaction between mapping and experiment [$F_{(1,38)}$=186.5, p<.0001]. The pattern of this interaction indicates that only in Experiment 6a was there a difference between the two mappings where the H_C mapping resulted in response times on average 59 msec faster than the L_C mapping. Although this interaction was not significant in the overall analysis by subjects, it reflects the pattern found in the individual subjects analyses for each experiment. For the predicted response by object compatibility interaction calculation of F*min* did not give a significant result [$Fmin$=3.43, $Fmin_{(.05,\ 1,61)}$=4.00].

6.4.4. Discussion Experiments 6a and 6b.

The most important result of Experiment 6b was the occurrence of a compatibility effect of the irrelevant object type on clockwise/anti-clockwise wrist rotation responses when these were executed whilst subjects viewed the objects. This compatibility effect was only observed for the clockwise compatible objects. Executing responses with the objects in view, rather than immediately afterwards, also had a number of other effects on the pattern of results. In contrast to Experiment 6a the effect of object compatibility was significant. The pattern of the significant two-way interaction between Response and Object Compatibility, however, explains the main effect observed (see Figure 6.6). Executing the responses with the objects in view would seem to be crucial to obtaining a compatibility effect, although it must be stressed that the pattern of means was very similar for both experiments and the overall ANOVA showed no interaction between the compatibility effect across experiments. In contrast to Experiment 6a no effect of mapping was observed when responses were executed in the presence of the object. As mentioned in the discussion of Experiment 6a this is probably a reflection of the different task constraints in each experiment. When responses were executed after object offset the task was a straightforward choice reaction time response to a tone stimulus. This may have exaggerated any effect of mapping as subjects would expect a tone after object offset and much of the variation in response times would be attributable to the ease of implementing the mapping rule. When responses were executed during object exposure, however, the tone occurred without a cue and whilst subjects were attending to the illuminated object. Rather than the mapping rule, it seems to have been the saliency of the tone cue itself that caused most variation in the response times.

The response by object compatibility effect observed is quite striking when one considers the task subjects were carrying out. They were instructed merely to attend to the object whilst it was in view - the actions they performed were determined solely by the tone stimulus that occurred either during or immediately after the illumination of the object. As in the previous experiments, with the exception of Experiment 1 where explicit object oriented actions were required, none of the subjects appeared to have any idea of the relation between the stimuli and their responses. Despite this the compatibility relation between the response required and the object they were attending exerted a small, but nonetheless significant, effect on their response latencies. This result provides important evidence for the view that merely attending to an object results in the activation of motor components of the actions it affords. Whilst the pooled data from both experiments did not find a significant interaction between the compatibility effect observed when the response was executed with the object in view or not, the separate analyses imply that the consistency, and magnitude, of the effect is greater with the objects in view. It would certainly seem plausible to suggest that the reason for this is the transient nature of the visuo-motor representations involved. This transiency is not necessarily the same as that involved in the decay of automatically activated spatial codes in the typical Simon effect (Hommel 1994b). There is no reason to suppose that the activation of visuomotor patterns that represent the affordances of the object decay shortly after they have been formed. Rather, they might be proposed to be transient in the sense that they are rapidly updated whenever the object or the motor systems of the observer change - a continuous property during normal visually guided actions. Such a view would implicate the lack of the visual presence of the object, rather than the longer response times, as the principle cause of the weakening of the effect in Experiment 6a.

The effects observed in Experiments 6a and 6b are quite immune from abstract coding interpretations based on dimensional overlap. In contrast to a property such as object orientation there would seem no way that the two object types could be conceivably coded as sharing a 'clockwise' or 'anti-clockwise' dimension. If there was a broad dimension across which the objects differed it was overall size - anti-clockwise compatible objects being, on average smaller than clockwise compatible ones. Overall size is one of the characteristics that go toward determining the compatibility relation as any object small relative to the hand must be grasped with an anti-clockwise wrist rotation. Moreover, in these studies the response relevant property was not even part of the same stimulus as that responsible for the compatibility effect. Traditional abstract coding accounts of SRC cannot, therefore, explain the result even with resort to the postulation of codes extracted across widely differing stimulus objects - a process in any case shown to be unlikely from the results of Experiment 4.

The final experiment aimed to extend the examination of the potentiation of actions by visual objects to the grip type component of prehension.

6.5. Experiment 7: Object affordances and precision-power grip responses.

6.5.1. Introduction

Experiment 7 used the same method as Experiment 6b to examine a different object-action relation. The affordance examined was that of grip type and the stimulus objects comprised those that would require either a precision grip or a power grip, if they were to be grasped. There is some neurophysiological evidence that cells in area 7a of the parietal cortex and inferior area 6 of the premotor cortex are sensitive to the type of hand shape required to grasp an object (Taira et al., 1990; Rizzolatti et al., 1988). More importantly some of these cells appear to be activated simply by viewing the object (DiPelligrino et al., 1992). Hand shape would seem to be a likely candidate, therefore, for a component of action that can be potentiated merely by viewing an object. Behavioural evidence also indicates that hand shape is a component of *explicit* goal directed actions that is planned prior to movement initiation (Klatzky et al., 1995), a property which reinforces the likelihood of such motor patterns being capable of being potentiated by the sight of the object even when no action has to be performed.

6.5.2. Method

Subjects

40 subjects took part in the experiment. All were students at the University of Plymouth and received £3.00 or course credit for their participation. All the subjects were right handed by self-report and naive as to the purpose of the study. None had participated in the previous studies.

Apparatus and Materials

The stimuli consisted in forty common objects listed in Table 6.7. Twenty had large opposition axes, such as a hammer or bottle, and would therefore require grasping using a power grip with the lower phalanges of the fingers opposing the palmar surface. The other twenty objects were all small relative to the hand or had thin principle axes such as a bottle lid or a pen, and would require grasping by a precision grip between the top most phalanges of the index finger and thumb. The stimuli were presented in the same apparatus as that used in the previous two experiments. The only difference in the apparatus used was the response device. This consisted in two components. The first was an aluminium cylinder 8 cm tall and 2 cm in diameter. Attached to the side of the cylinder was a small section of aluminium tubing which was hinged to the top of the cylinder and attached to a pressure switch at the base of the cylinder. It thus acted as a lever that caused the pressure switch to trigger when the hand squeezed the cylinder. The second component consisted of a pressure switch 1 cm square and 4 mm thick that was taped to the inside tip of the subjects thumb. A diagram of the device is shown in Figure 6.10. This triggered a response when it was squeezed between the index finger and thumb. The two types of response thus mimicked power and precision grips[17]. The power grip response device was covered in a thin layer of cotton to prevent slipping.

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[17] Because the index finger and thumb had to be used for the precision grip response it was not possible to allow the index finger to take part in the power grip response even though it would typically be used. However a grasp between the palm and the middle, ring and little finger still closely resembles a typical power grip.

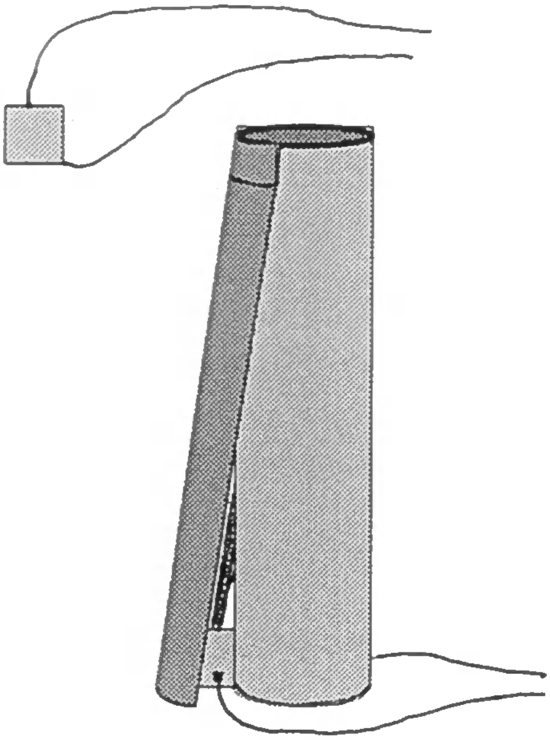


Figure 6.10. A diagram of the device used to monitor precision and power grip responses in Experiment 7.

Table 6.7. List of stimuli used in Experiment 7.

Objects compatible with a precision grip.

Screw
Nail
Pencil sharpener
Bottle top
Coin
Rubber
Drawing pin
Match box
Match
Washer
Pencil
Pen
Safety Pin
Bolt
Screw
Bolt
Pen Top
Key
Key
Clothes peg

Objects compatible with a power grip.

Hammer
Claw Hammer
Wooden Mallet
Bottle
Saucepan
Frying Pan
Wooden Mallet
Saucepan
Frying Pan
Rolling pin
Wooden Block
Jug
Coffee Pot
Bottle
Large Jar
Large Screwdriver
Wire Brush
Metal Tube
Dust Pan
Metal Cylinder

Procedure

The procedure was identical to that of Experiment 6b (tone cues were given with the objects still illuminated) with the exception of the responses and the mapping rules assigned to subjects. Subjects were instructed either to make a response by squeezing the cylinder with the fingers surrounding it (excluding the index finger) to the high pitched tone and one by squeezing the pressure switch between the index finger and thumb to the low tone or vice versa. The red warning light served the same function as in the previous experiments except that it flashed on and off, halting the progression of trials, if subjects failed to release either switch after making a response. As before they were told that they could halt the progression of the experiment at any time by deliberately keeping either of the switches depressed. Most subjects had little difficulty in making responses on the device after they were given sufficient practice.

6.5.3. Results

Response times

The data from two subjects was discarded as their error rates exceeded 10%. For the rest their condition means were computed after discarding reaction times more than two standard deviations from their overall means. These were subjected to a mixed ANOVA with the within subjects factors object compatibility (precision or power) and response (precision / power) and the between subjects factor mapping rule (high tone precision / low tone power (H_PRE) or the reverse (H_POW). This analysis revealed significant main effects of response and mapping. Precision grip responses (M=398.7) were executed faster than power grip responses (M=417.6), [$F_{(1,36)}$=12.94, p=.001]. The main effect of mapping revealed that the assignment of the high pitched tone to precision grip responses and the low tone to power responses resulted in faster response times (M=380.4) than the reverse mapping (M=435.9),[$F_{(1,36)}$= 4.57, p=.039]. These two factors interacted (see Figure 6.11). The pattern of the interaction suggests that there was still an important main effect of mapping but that the main effect of response was largely attributable to an advantage for the precision grip responses in the H_PRE mapping [$F_{(1,36)}$=8.43, p=.006]. The most important result, however, was that the predicted interaction between object compatibility and response was significant. For precision compatible objects precision grip responses tended to be executed faster (M=396.7) than power grip responses (M=400.8), whereas for power compatible objects power grip responses tended to be executed faster (M=410.1) than precision grip responses (M=425.1), [$F_{(1,36)}$=7.1, p=.011]. This interaction is displayed in Figure 6.12. The pattern of error rates indicates the absence of any speed-accuracy trade offs.

Pairwise comparisons of the interaction between response and object compatibility (Newman-Keuls) indicated that the difference between precision and power grip responses was only significant for the power compatible objects [$Q_{(2,36)}$=4.2, p<.01, $Q_{(.01,\ 2,36)}$ = 3.84]. Interpretation of the compatibility effect is complicated because, as in the previous experiments, there was also a highly significant three-way interaction between this and mapping [$F_{(1,36)}$=17.23, p<.0001]. This is displayed, broken down by mapping, in Figure 6.13.

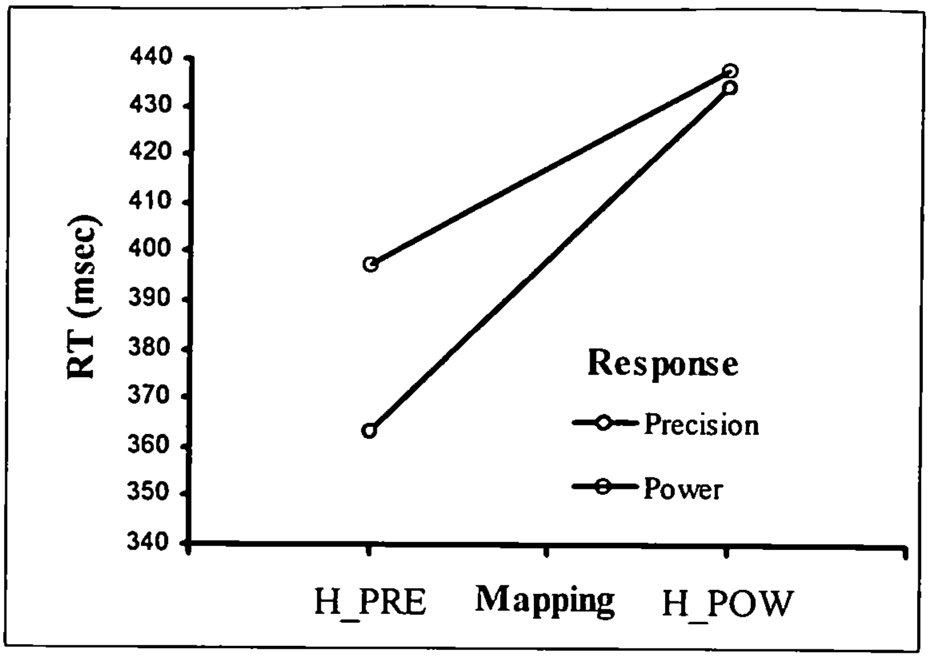
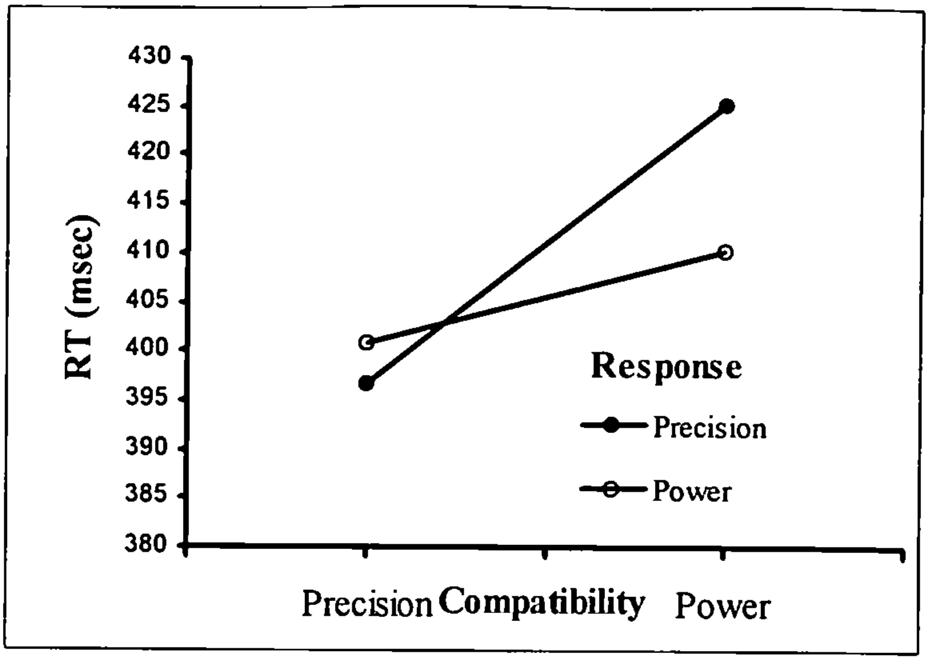


Figure 6.11. Response by mapping interaction for Experiment 7.

Table 6.8. Mean RT, standard deviations and (% errors) for Experiment 7 by Object compatibility, response and mapping.

	Precision Responses		**Power Responses**	
Mapping	**Precision compatible**	**Power compatible**	**Precision compatible**	**Power compatible**
H_PRE	**354.3** 59.6 (2.8)	**372.5** 63.7 (2.5)	**412.79** 67.5 (4.7)	**382.19** 63..9 (3.8)
H_POW	**439.1** 88.9 (3.4)	**429.0** 88.5 (3.7)	**437.4** 107.3 (3.8)	**437.9** 108.0 (4.2)



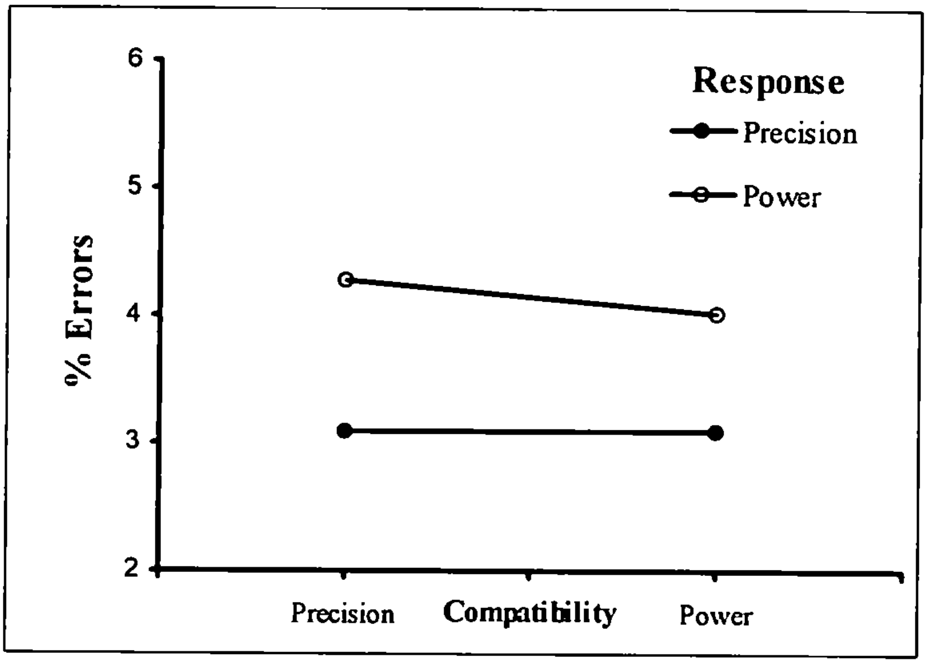
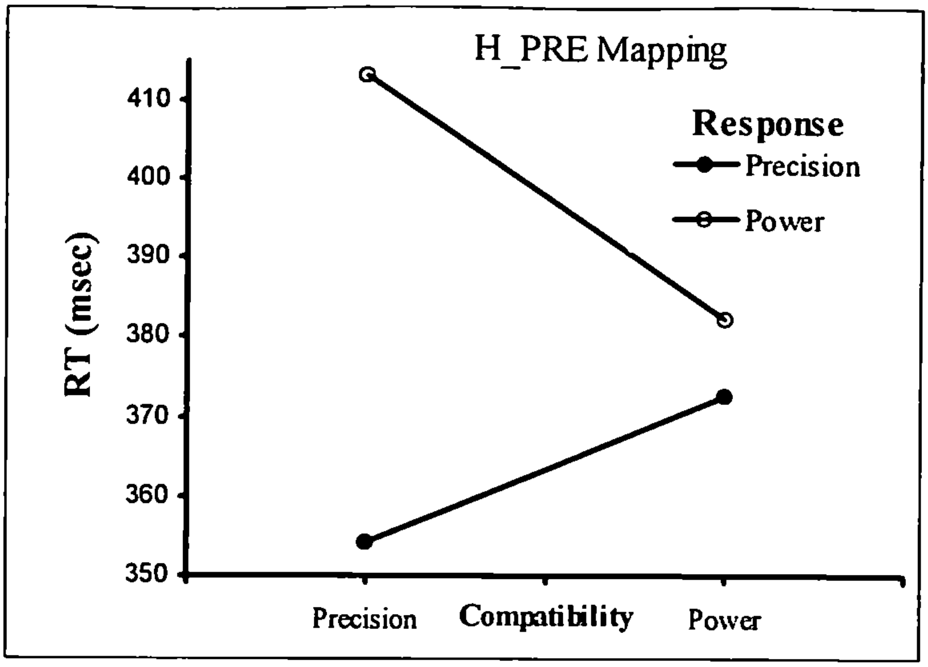


Figure 6.12. Mean RT and % errors for Experiment 7 by response and object compatibility.



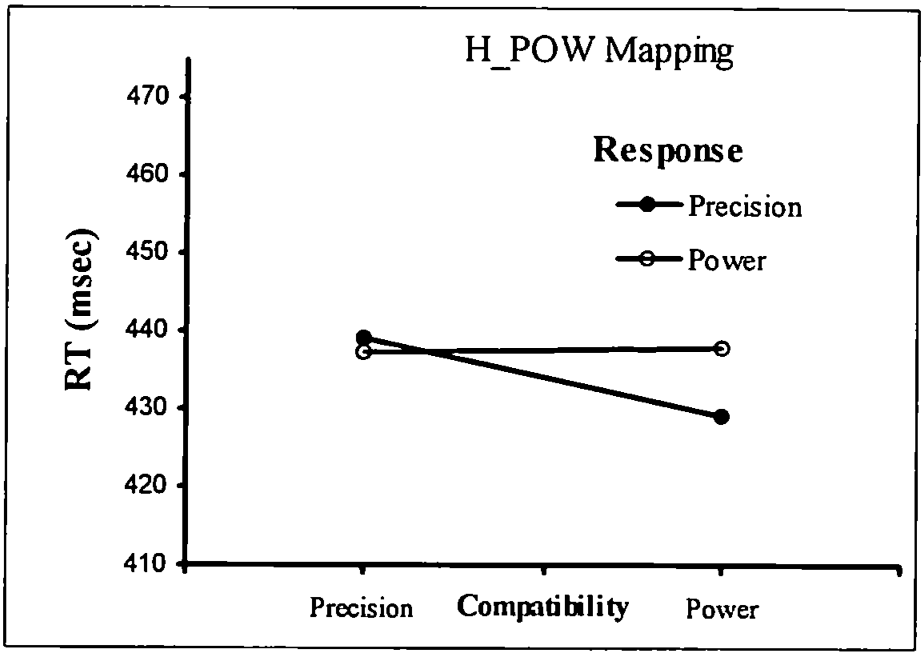


Figure 6.13. Mean RTs for Experiment 7 by Response, object compatibility and mapping.

As can be seen from a comparison of the graphs in Figure 6.13 the compatibility effect appears to be confined to the H_PRE mapping. The relevant data is presented in Table 6.8. Analysis of the simple interaction effects broken down by mapping showed that the response by object compatibility effect for the H_PRE mapping was highly significant [$F_{(1,18)}=19.52$, $p<.0001$] whereas for the H_POW mapping it did not approach significance [$F_{(1,18)}=1.36$, $p=.259$]. For the data from the H_PRE mapping Newman-Keuls follow up tests were carried out on precision and power grip responses in the presence of the two types of objects. For precision grip responses the 18.2 msec advantage for responses executed whilst attending to a precision-compatible object was significant [$Q_{(2,19)}=3.29$, $p<.05$; $Q_{(.05,\ 2,\ 19)}=2.96$], and also for power grip responses the 30.6 msec advantage for responses executed whilst attending to power-compatible objects was significant [$Q_{(2,19)}=5.54$, $p<.01$;$Q_{(.01,\ 2,\ 19)}=4.05$].

Error rates

An Analysis of subjects error rates did not find any significant effects. The average error rate for the experiment was 3.6% and the pattern of errors very similar to that of response times.

Materials Analysis

Analysis of the data with objects as a random factor revealed a similar pattern of effects as that of the subjects analysis. The main effects of response [$F_{(1,19)}=33.49$, $p<.0001$] and mapping [$F_{(1,19)}=336.1$, $p<.0001$] were highly significant. The predicted interaction between response and object compatibility was significant ($F_{(1,19)}=10.91$, $p = 002$). As in the subjects analysis the interaction between response and mapping was also significant

($F_{(1,19)}$=18.64, p<.0001) as was the three-way interaction between response, object compatibility and mapping [$F_{(1,19)}$=18.63, p<.0001]. All the effects showed identical patterns of means to those shown for the subjects analysis. Calculation of F*min* for the predicted interaction between response and object compatibility gave a significant result [F $min_{(1,70)}$ = 4.31, ($F_{(.05,1,70)}$ = 4.00)].

Supplementary analyses

As in all the previous experiments the subject data was analysed using Median RT and Log RT. Both analyses confirmed the results from the original analysis using 2sd cut-offs. The main effect of response was significant using both medians [$F_{(1,36)}$=12.16, p = .001] and Log RT [$F_{(1,36)}$=14.61,p = .001]. The effect of mapping was only significant in the analysis using Log RT [$F_{(1,36)}$=4.36, p=.044] but approached significance using Median RT [$F_{(1,36)}$=4.41, p= .052]. Median RT also did not find the response by mapping interaction significant [$F_{(1,36)}$=1.65, p=.207] whereas the analysis with Log RT found this effect to be highly significant [$F_{(1,36)}$=10.32, p=.003]. Importantly both analyses confirmed the predicted interaction between response and object compatibility [$F_{(1,36)}$= 4.41, p=.043, Median RT; $F_{(1,36)}$=6.5, p=.015, Log RT]. The three-way interaction between response, object compatibility and mapping was significant in both supplementary analyses. For Median RT [$F_{(1,36)}$=9.52, p=.004] whilst for Log RT [$F_{(1,36)}$=17.97, p<.0001].

6.5.4. Discussion

The most important result in Experiment 7 was the finding of a significant compatibility effect between precision/power grip responses executed in the presence of precision/power compatible objects. The significant value for F*min* implies that the results is very unlikely to be restricted to the objects used in the study. The highly significant interaction between this compatibility effect and the mapping rule assigned to subjects complicates the interpretation. This interaction suggests that the compatibility effect was restricted to one of the mappings (the High tone - precision grip response), a pattern similar to that found in Experiments 6a and 6b where the compatibility effect of object type on responses was present mainly in the low tone-clockwise response mapping. The main effect of mapping lends itself to an interpretation based on the salient features model (Weeks & Proctor 1990). Performing precision grip responses to the high-pitched tone and power grip responses to the low tone appears to have been an easier task than the reverse mapping. This, no doubt, results chiefly from some natural tendency to associate the high pitched tone with a 'precise' response and the low tone with a less precise response. Such an interpretation seems intuitive, at least, although as in the previous experiments effects of mapping are to be expected but of only minor interest (Experiment 5 excepted). Returning to the two effects of interest the predicted interaction between response and object compatibility was significant, but mainly because of a highly significant effect in the H_PRE mapping. Why this should be so is not clear. Explanations based on the relative speed of responses executed in the two mappings are not consistent with the data from the previous experiment, in which the mapping rule with the longest overall RT was the one in which the compatibility effect predominated. In Experiment 7 the H_PRE mapping, in which the compatibility effect was observed, had response times considerably shorter, on average, than the alternative mapping. Because of the remarkably similar pattern of results across all of the last three experiments - a compatibility effect of object affordance on responses occurring for one of the mapping conditions only, a tentative, post hoc, hypothesis to account for it is offered in the next section. Despite the complications that arise from the existence of higher order interactions the action potentiation hypothesis gains some further, quite striking, evidence from the effect observed in Experiment 7. As before subjects were simply attending to objects compatible with one of two grasp types. The object displayed was completely irrelevant to the task explicitly given to the subjects - they were not required to make any actions toward the objects - simply to view them and make responses based on the pitch of the tone stimulus. As with Experiments 6a and 6b the fact that *no* object property was relevant to response selection makes the effect observed much harder to explain from an abstract coding account of SRC.

6.6. General Discussion

The experiments reported in this chapter extend the evidence for the potentiation of actions to two further components of prehension, wrist rotation and grip selection. The results of Experiment 5 imply that more than the low level affordances are activated by merely viewing an object. In the introduction to Chapter 4 it was proposed that action potentiation takes place principally at the level of 'micro-affordances' - those affordances generated by the visually derived structural properties of the object. This proposal was based on the notion that the dorsal visuomotor stream is functionally quite separate from the ventral stream. Only within the ventral stream is a representation suitable for recognition made available. Action potentiation by the dorsal stream is proposed to arise from the relation between the physical properties of the objects and the motor system. Higher level affordances, based on object function and its everyday use, are less likely to be activated by this route. The results of Experiment 5 suggest, however, that high level affordances may be just as capable of entering into compatibility effects, with the result that a property such as object inversion interacts with the low level affordances based purely on the shape description of the opposition space embedded in the object. Such processes do not necessarily depend on semantic mediation but may arise from a direct route between the shape description of the object and an associated action. Just such an account has been proposed by Humphreys and colleagues (Riddoch & Humphreys, (1987); Riddoch, Humphreys & Price, (1989); Pilgrim & Humphreys 1991) from neuropsychological evidence (see chapter 2) and, more recently, by Rumiati & Humphreys (1996) from normal subjects. In the latter study Rumiati & Humphreys had subjects perform actions to object names or pictures under time pressure conditions. The main thrust of their findings was that the types of errors produced depended on the mode of the stimulus presentation. When presented with pictures of objects so called 'visual' errors predominated over visual and 'semantic' errors. In contrast, when presented with object names semantic and semantic-visual errors predominated. Visual errors are those in which the action performed under time pressure reflected an appropriate action to a visually, but not semantically, similar object - for example making a sawing or cutting action to a comb. An example of a semantic error would be making a hammering gesture to a saw. They argue that this further supports the neuropsychological evidence for a direct route from vision to action. Their data do not provide evidence for the *automatic* activation of afforded actions as subjects were explicitly instructed to make actions to the objects. The existence of such a route makes available a mechanism whereby high level affordances could be activated during visual processing.

The results of Experiments 6a and 6b suggest that when object inversion is not manipulated a compatibility effect between responses and object type does emerge. Though the pattern of means was remarkably similar in the two experiments the straightforward compatibility effect between object type and response was only significant, and of greater magnitude, when the responses were executed with the object in view. Such a finding, it was argued, reflects the transience of the representations employed by the visuo-motor system. The effect of object type was, however, restricted to clockwise responses in Experiment 6b, as it was also in the combined data from both experiments.

The consistency in the patterns of results in Experiments 6a and 6b suggests that the restriction of the predicted compatibility effect to one of the mapping conditions is more than a mere coincidence. This point is made even more apparent by the occurrence of a similar pattern in Experiment 7 where the response by object compatibility effect was confined to the mapping condition in which high pitched tones demanded precision grip responses and low pitched tones power responses (the H_PRE mapping, see Figure 6.13). To understand why this pattern should emerge is difficult. An interpretation based on the average response times for the different mappings is not consistent with the pattern of effects, as the mapping within which the compatibility effect occurred had the longer average response times in Experiments 6a and 6b but the shortest in Experiment 7. If a consistent pattern had emerged, such that the mappings producing the shortest response times were also those in which the compatibility effect occurred, it could be taken as evidence that automatically generated action codes are subject to relatively rapid decay, as is the case for location codes in abstract Simon paradigms (e.g., Hommel, 1994a, 1994b). An explanation that does make sense of the pattern takes account of the fact that there appears to be a tendency across all three experiments to associate smaller objects with the high pitched tone and larger ones with the low pitched tone - this relation being particularly marked in Experiment 7 where the size difference between the two classes of objects was, by the nature of the compatibility relation explored, greatest. The effects observed may be due, in part, to the existence of a degree of (cross modal) stimulus-stimulus congruence between the stimulus objects and the stimulus tones. If there is a natural tendency for smaller objects to be associated with high pitch tones and larger objects with low pitched tones then the pattern of the observed data makes sense. The pattern of data do in fact support this - there being a reasonably consistent advantage for the pairing of high pitched tones with the smaller objects (anti-clockwise compatible in Experiments 6a and 6b, precision compatible in Experiment 7). Under this hypothesis one would expect the effect of object compatibility to be partially cancelled out when large objects are paired with high pitched tones and small objects with low pitched tones, which is exactly what happens in

Experiments 6a - 7. In Experiment 6a and 6b a compatibility effect is expected when clockwise responses are paired with the (relatively large) clockwise compatible objects and vice versa. Under the L_C mapping the stimulus-stimulus congruence between tones and the objects is preserved on compatible trials whereas in the H_C mapping it is not. The same is true for Experiment 7, where the congruency relation is preserved on compatible trials in the H_PRE mapping but not in the H_POW mapping. This postulation is, of course, highly conjectural but does make sense of the pattern of results and is offered because of the remarkably consistent pattern observed.

The results of Experiments 6a-7 provide evidence that all of the principal components involved in prehension can be potentiated by the sight of a graspable object within the reaching space. The size of the reaction time benefit associated with a compatible stimulus-response pairing is relatively small and quite sensitive to the particular task constraints such as the mapping rule assigned to subjects. Nevertheless, potentiation is detectable using a reaction time paradigm and a detailed investigation into the precise circumstances under which it arises awaits further investigation. The findings confirm Michaels' (1988) conjecture that a reaction time paradigm could be a valuable method for detecting those actions most afforded by an environment over other less afforded actions. The results go much further than this, however, in that the relation between the components of action and the stimuli were never made explicit to the subjects. By making responses share only a component of an action, the relation between that response and the action of which it was a part, always remained hidden. As such, the compatibility effects observed implicate the involvement of the visuo-motor and motor systems in the visual representation of an object even when no explicit intentions to act, and therefore to compute components of the intended action, have been formed.

7. Chapter 7 : Discussion and conclusions

The experimental work in this program aimed to establish that simply viewing an object results in the potentiation of the actions it affords. In this chapter the extent to which they do so will be discussed, together with the notion of action potentiation in general and the implications for theories of visual representation and action. Finally, some of the possibilities for further research are examined.

7.1. Action potentiation and affordances

The action potentiation hypothesis has two major parts. First, that the actions an object affords are an intrinsic part of its representation. Second, that the way object affordances are represented, directly involves the visuomotor system. It is in virtue of the first component that the actions an object affords are represented *automatically* - where automatic in this case refers strictly to the notion that explicit intentions to make an action need not be instantiated in order for the affordance to be represented. It is in virtue of the second component that an action is *potentiated* and, as a result of this, enables its existence to be examined by using the action, or component of it, as a response in a choice reaction time paradigm. There are several necessary prerequisites that the potentiation of the actions an object affords must fulfil if it is to be examined using reaction time methodology in general, and an SRC framework in particular. One of the most important is that object affordances are not simply *detected* as possibilities for actions, but actually activated by the involvement of the motor system in their representation. It is conceivable that an affordance of an object could be represented in a manner that had little or no influence on the speed with which a component of that action was initiated when not directed to the object. To take Warren's (1984) study on the 'climbability' of stairs as an example it is possible that stair climbability is simply detected without any potentiation of a climbing action. Such detection would not necessarily result in any speed advantage for producing a component of a climbing response. This is where the action potentiation account differs from the ecological one. Although the work on vision and action undertaken within the ecological approach has often emphasised the scaling of affordances to the effector systems of the observer, the process by which this is achieved has received little attention. Under the potentiation account the representation of affordances directly involves the visuomotor system. A consequence of this is that not only are afforded actions potentiated but they are also scaled to the effector systems of the perceiver. It is argued that the perceptual systems of organisms are geared to pick up visual information at an action relevant spatial scale. Thus in Warrens (1984) study the perception of climbability involved the detection of a metric -the ratio of stair riser height to leg length. Subjects were very accurate in perceiving when the ratio of stair riser height to leg length exceeded some critical value. The detection of the affordance of climbability is scaled, as it has to be, to the physical properties of the perceiver (one could argue, however, that people simply learn a relationship between perceived height at a certain distance and past instances of climbability). In this sense the ecological approach stresses information detection rather than representation- the emphasis is on what visual properties in the environment convey action relevant information to the observer. More than this, the approach, also emphasises the dynamic gearing of action systems to specific visual properties or invariants. To emphasise, (perhaps over simplistically), the difference between an information processing approach and an ecological approach to the problem of visually guided action one can use the task of catching a ball. A computational approach to this problem might typically involve computing the projected trajectory of the ball and determining the position the hands would have to be in to successfully catch it. The trajectory would in this case have to be more or less explicitly calculated. In contrast the ecological approach would seek to determine if there was a perceiver-ball relation that remained constant only under conditions that would result in being in the correct place to catch the ball. Indeed the evidence from analysing real catching movements suggests that people do in fact constantly monitor a perceiver ball relation rather than determine where they will have to be to intercept the ball, that is they move so as to keep a perceptual relation within certain limits (see McLeod & Dienes, 1996). Essentially the two approaches are *not* inextricably opposed - the ecological approach has the advantage of starting from a point of view more likely to find simpler non-computational solutions to the problem (but they are non-computational often only because of the level at which they are aimed - specifically : what information is used to guide the action rather than how does the organism extract and use that information). Indeed many newer and more biologically plausible computer models of visually guided action do the very same thing. Rather than explicitly calculating the trajectory the arm needs to go through to reach a target, and then translating this computation to a series of muscle commands (both processes being ill defined and extremely complex even given a set of constraints to operate within) these models rely on learning the relation between muscle lengths and target position (e.g. Bullock & Grossberg 1988) or whole postures based on joint angles (Rosenbaum et al., 1995). In a biological system many of the problems of translating a desired end position to a series of muscle commands to bring it about can be solved without explicit computation. In Bullock & Grossberg's (1988) model, for example, this is achieved by each muscle group being changed by an amount proportional to the difference between their present length and desired final length. This process naturally results in trajectories with approximately straight line hand paths, a characteristic typical of human and primate reaching movements. Such learning based models of visually guided action are not, in principle, so far removed from ecological models. The major difference really lies in the kinds of questions asked by the two approaches. Biologically based models aim to understand implementational questions, whereas ecological models aim at an understanding of the kinds of (visual) information used by perception-action systems. The notion of action potentiation in many ways bridges the gap between the two approaches. In as far as it involves the *representation* of visual objects it differs from ecological approaches, but nonetheless keeps as a central concern the relevance for action of visual object properties. It remains an information processing account in so far as it centres around questions of representation and implementation. The approach is, however, similar to the ecological approach in as much as the kinds of representations proposed directly involve the action systems of the perceiver, their 'effectivities' in the ecological sense.

The experiments carried out in this program of research aimed to establish that the visual representation of an object involves the representation of its affordances *in a particular way*. Specifically it was proposed that the affordances were represented by the direct activation of the visuomotor systems to which they were linked. By using the visuomotor system to represent certain object properties (those which relate to the affordances of the object) certain representational problems are simplified. The question of frames of reference is a case in point. Objects need to be represented in a manner that not only allows for successful recognition but also for successful interaction. The starting point for this work was the assumption that objects are represented in a manner that enables *both* tasks to be achieved. This requires that multiple representations of object properties exist simultaneously and in different reference frames. For recognition it may be necessary to form an object centred representation along the lines of the 3D model proposed by Marr (1982) or according to its breakdown into constituent viewer-invariant components (Biederman, 1987). In this way the relation between the component parts of the object remain invariant across changes in viewpoint. For successful interaction, however, an object centred representation is a hindrance not a virtue, as critical information about the relation between the object and the observer is lost. In a broad sense of the term the object requires representing in a viewer centred frame of reference, a property proposed by some authors to form one of the bases that differentiate the representational processes operating in the dorsal and ventral visual processing streams (e.g. Goodale & Servos, 1992). The term 'viewer centred' has to be treated in a broad sense because actions require the relation between the object and the many components of the effector systems to be specified. One could say that many separate systems, such as the arm, the hand, and the fingers all need to 'view' the object, and as such employ separate viewer centred schemes, 'viewer-centred' thus referring to a large number of body-centred reference frames rather than a single one based on eye position. If this was the way that object properties were represented even in explicit goal directed acts, then a multitude of separate representational schemes would all need to feed information into the separate effector components. The complexity of such a scheme vanishes, however, if, instead of employing a host of purely *visual* representations of the object under different reference frames, the object properties were, instead, represented directly within the visuomotor system. This could be achieved by processes not unlike those proposed by Bullock & Grossberg's (1988) model. A single viewer centred representation (in their model this is assumed to based on a head-centred frame, similar to the implicit head centred frame in Zipser & Anderson's (1988) simulation of PPC cells) of the object, could activate target position commands for all the effector systems needed to bring about a successful reach and grasp. Such target position commands would arise by a continually updated learning mechanism based on successful interactions with objects. The only difference between this scheme and that proposed by those authors is in the idea that such implicit representations of object properties would be activated regardless of an explicitly formed intention to make an action toward the object. Instead of having to represent object properties in arm, hand and finger centred co-ordinates that were available to be translated to appropriate muscle commands, the representation would actually consist in the activation of those muscle commands minus the 'go' signal that results in their execution.

A second virtue of the action potentiation account is that it makes information about the possibilities for action available to the perceiver. Possibilities for action, are, of course, one definition of affordances in the ecological sense. However the mechanism by which this is achieved is unspecified in the ecological account and in fact not deemed a relevant question[1]. It is proposed that the possibilities for action are directly perceived by virtue of the organism 'picking up' action relevant invariants in the optic array. In contrast, the view advocated here is that the involvement of the action system in representing the properties of visual objects results in the availability of action relevant information. Whether or not an action is possible and, if it is, how to execute it, is made available by having the visual properties to which that question is addressed actually represented in visuomotor terms. This touches on the area of motor imagery. One of the consistent findings here is that the motor system is directly involved in tasks involving judgements about actions (see Jeannerod, 1994 for a review) as well as those involving purely perceptual judgements about object properties that are directly associated with the action system. An example of the latter is a study by Parsons (1994) in which subjects had to determine the handedness of pictures of the left and right hands. Their judgement times consistently reflected the actual time needed to rotate their hands into the position of the depicted images - a result that also depended on the starting position of their hands. Even though the judgements to be made were purely perceptual and did not involve performing any action, the motor system appeared to play a significant role in their determination. As mentioned in Chapter 2 single cell recording studies of monkeys have suggested that many of the neurones activated

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[1] It is irrelevant in as much as the ecological approach is essentially behaviouristic.

during reaching and grasping are also activated when the animal merely observes another animal (or even the experimenter) perform the same action (DiPelligrino et al., 1992).

7.1.1. The activation of *components* of action.

Because the methods used to evaluate the action potentiation account involved subjects making responses that involved a component only, of an afforded action, it is necessary that the activation of the various motor systems involved in the action do not wait until part of the movement has unfolded. This question is not one of parallel versus serial programming stages. It is instead the question of what components of action are planned before movement initiation and what components only unfold as part of the movement itself. If a serial model is assumed then one would expect reaction time effects to be limited to the first stage of the motor programs involved in the afforded action. The organisation of the visuomotor system would suggest, however, that a parallel model is more appropriate, with different object properties feeding information forward to different effector systems simultaneously. The separateness of the various object-effector relations has led some authors (e.g. Jeannerod, 1994) to propose that object properties are not actually 'bound' together to form a whole. As long as each effector system has the relevant information there does not need to be a unified whole object in order to successfully guide actions. Separate representations of the effector relevant information suffice, in marked contrast to the kind of unified description required if the object is to be identified. This approach, however, still involves multiple representations of the component object properties that feed forward information to the relevant effector systems. As such it is not as efficient as the scheme proposed by Bullock & Grossberg (1988) in which the various effector systems are driven to their final end position on the basis of a single viewer centred representation of the target object. Separate effector-object relations are only implicit in this model. The crucial point with regard to action potentiation is that on this account all the components of an afforded action would be simultaneously activated. This follows directly from the way the trajectory is implemented. All the muscle groups involved simultaneously move toward the target position. This model does not, of course, say anything about the state of the action system when an object is viewed *without* an explicit intention to reach toward it. The mechanism is, nevertheless, a possible one for implementing action potentiation.

7.2. Experimental summary

7.2.1. Object orientation and hand choice.

The first experiment was carried out in order to ensure that an object property such as orientation can influence hand choice when the task is to grasp the object. This was principally a pilot study aimed at ensuring that factors which intuitively affect the ease with which an object can be grasped by a particular hand do produce a measurable effect under choice reaction time conditions. A similar study by Klatzky et al. (1995) had shown that factors affecting the hand shapes used to grasp objects exert measurable compatibility effects on movement initiation times. Experiment 1 aimed to extend those findings to object orientation and hand selection. The results were quite straight forward. When objects were oriented so as to be more easily grasped by one hand, that hand was faster initiating a reaching movement to the object. As mentioned in the discussion of Experiment 1 the occurrence of this compatibility effect does not, by itself, imply that the initial exposure of the oriented object primed a particular hand of response. The cost and benefits associated with the compatibility of the object with the cued hand could have arisen *after* the tone cue was given. In this case the compatibility effect would amount to a difference in the time courses of planning reaching movements to objects more or less compatible with the chosen hand. Locating the source of the effect here seems unlikely, however, given the organisation of the visuomotor system and the fact that subjects knew that they would have to reach out and grasp the object. Furthermore the results of Experiment 3, where no explicit reaching movements were called for, and yet compatibility effects arose, strongly suggests that the initial exposure of the object was actually priming a particular hand of response. Consequently Experiment 1 can be taken as fairly safe evidence that under conditions in which reaching movements are actually part of the task, the orientation of an object primes the most compatible hand of response.

Having verified the influence of object orientation on hand selection the next three experiments used this object property to specifically examine the action potentiation account. In these and all subsequent experiments the action relevant property of the object was always irrelevant to the task. The tasks all consisted in a variant of a typical SRC experiment although classifying them into a particular kind is difficult. A case could be made for their classification as Type 3 ensembles in Kornblum at al.'s (1990) terminology in which there is dimensional overlap between the irrelevant stimulus and response dimensions and no overlap between the relevant dimensions. Such a classification, however would have to be employed very loosely as there is no evidence that the irrelevant stimulus dimensions really overlapped with the response dimensions. Experiment 2 employed a selection of real objects as stimuli oriented to the left or right, so as to be compatible with either a left or right hand reach and grasp movement. In this case no compatibility effect of the irrelevant left-right orientation on hand of response was found. Before concluding that this constituted a refutation of the action potentiation account a possible reason why there was no effect was suggested. This reason centred on the role of attention in the formation of spatial codes that give rise to typical Simon effects. In Experiment 2 the objects were chosen with two aims in mind. First they had to be objects whose orientation would affect the ease with which they could be grasped by either hand. Second they needed to be relatively light and capable of being easily inverted by the experimenter, as inversion was the response relevant stimulus dimension. Unfortunately this resulted in a serious confound. In almost every instance the feature of the object that specified its inversion was located at one end of the object and this was always opposite the graspable end. Given the importance of the locus of attention for producing spatial codes (e.g. Nicolletti & Umiltà, 1989) it was quite probable that a spatial code of opposite value to any response code activated by the graspability of the object would be produced. If this was indeed taking place then any effect of the potentiation of the hand of response most suited to grasp the object would be cancelled out. Such an effect would be exaggerated, it was argued, by the fact that subjects would also be restricting their attention to a small region of the object that did not include the *grasp* relevant features. The reasoning is, of course, post hoc, but it must be taken seriously as the principle explanation of left-right spatial compatibility effects of an irrelevant stimulus dimension is attentional (Stoffer & Yakin, 1994; Nicoletti & Umiltà, 1989; 1994).

In order to provide a better test of the effects of object orientation on hand of response Experiment 3 used stimuli whose inversion, (this again being the response relevant dimension), was specified by more global object properties. Photographs of objects were used as they could not easily be inverted under experimental time pressure. The results were clear. When hand of response was cued by object inversion the irrelevant orientation of the object produced a highly significant compatibility effect. If the object's inversion cued a right hand response these were executed faster if the object was also compatible with a right hand reach and grasp movement and vice versa for left hand responses. Regardless of the interpretation of the effect the results of Experiment 3 provide the first case of a 'Simon effect' from a selection of widely differing natural stimuli. They are in complete agreement with the action potentiation hypothesis, but in order that this interpretation be fully acceptable Experiment 4 was carried out in order to rule out the most plausible alternative explanation. Rather than object orientation potentiating the hand most compatible with a reach and grasp movement it could be producing left-right spatial codes of the sort automatically produced in typical Simon paradigms, in which the stimuli varies on an irrelevant spatial location dimension. If this, rather than action potentiation, was responsible for the effect in Experiment 3 then redoing that experiment with responses executed by the fingers of a single hand should have little if any effect on the pattern of results. What matters for the Simon effect is the *relative* left-right coding of the stimuli and responses. Relative left-right response codes are still present when then responses are executed by the index and middle fingers of the right hand. The results strongly supported the action potentiation account. When left-right responses were made to the same stimuli but using the index and middle fingers of the same hand no compatibility effect of object orientation emerged. This finding was strengthened by an overall analysis of the two experiments which showed that the difference in the compatibility effect across experiments was significant. It is highly unlikely, therefore, that the results of Experiment 3 can be attributed to a typical Simon effect arising from the abstract coding of object orientation. The latter would assume that left-right object orientation automatically produces left-right *stimulus* codes that produce a compatibility effect in virtue of their overlap with the left-right response dimension. If this was the case then the same pattern should have been observable in Experiment 4. This result is important for two major reasons. First of all it provides convincing evidence in favour of the action potentiation account. If object orientation was not automatically producing left-right spatial codes but was, at the same time, exerting a compatibility effect on responses executed by the left and right hands, it implies that something other than an abstract stimulus code was influencing responses in Experiment 3. The only property that consistently varied with orientation was the graspability of the object by a particular hand. That this relation resulted in a response time benefit implies that the grasp compatible hand was actually being potentiated. The second reason that the result is important concerns the nature of the codes formed from a collection of natural objects. As noted in the discussion of Experiment 4 the absence of an effect here implies that object orientation does not easily get assigned an abstract left-right stimulus code in the way that, for instance, stimulus location does, in typical Simon paradigms. What makes up a left or right orientation varies for each individual object it is not immediately available as an obvious stimulus feature. One needs to bear in mind here that the ease of referring to the objects as left or right oriented reflects the explicit knowledge of the relation between this and graspability - knowledge not available to the subjects performing the experiment. It is only with reference to this relation that a simple binary left-right classification becomes apparent. This property is pertinent to all the experiments reported here. Whilst the objects in each experiment were not randomly chosen, from the collection of all possible objects, they can, nevertheless, legitimately be said to represent random collections from those populations having structural features that systematically affect the affordances mimicked by the responses (i.e. in Experiments 3 and 4 the population of objects whose orientations can be chosen to selectively favour a grasp by one or other hand). The characteristics of the objects that determine their affordances do not consist of a binary visual property that maps onto the binary response. In typical Simon paradigms the stimuli *do* possess this property - they are either to the left or right of a reference point (or, with symbolic displays they might consist in either left or right pointing arrows). The lack of an easily codable binary property from collections of natural objects makes it more unlikely that conventional SRC explanations can account for any compatibility effects observed. This is even more the case in the experiments reported here, given that subjects were never made aware of the relation between the object properties and their responses. In previous SRC experiments that have used more natural stimulus types (e.g. Michaels 1988) subjects were actually responding to the action relevant visual property on half of the trials. This strategy would make the action relevant stimulus property much more salient a feature, even in blocks of trials in which responses were determined by some other property. Employing an experimental strategy that never made the relation between object properties and responses explicit provides a much stronger test of the proposal that actions are activated by object affordances, regardless of the intentions of the subjects.

7.2.2. The direction of wrist rotation and object compatibility.

Wrist rotation cued by object inversion.

Experiments 5-6b examined a different object-response relation. The affordance that was made to vary with the object set was the direction of wrist rotation required to grasp the object. In Experiment 5 the direction of wrist rotation was determined by object inversion, as it was in Experiments 3 and 4. Under the action potentiation account clockwise wrist rotation responses would be expected to be executed faster when the object was compatible with a clockwise wrist rotation and vice versa for anti-clockwise rotations. In contrast to Experiment 3 this pattern was not observed. Instead an interaction between the mapping condition and the clockwise or anti-clockwise compatible objects was found. This result does not fall into any easily interpretable category from the standpoint of existent SRC research. The latter offers several possible interpretations of *main* effects of mapping - indeed investigating the advantages and disadvantages of mapping rules is one of the major branches of SRC research. It does not offer much insight, however, into the reasons why there should be an interaction between the mapping rule and the class of objects defined by their affordance for grasping with a particular direction of wrist rotation. The results do make sense, however, if one takes account of the effect of the object property (inversion) used to cue the responses. The explanation is post hoc but is consistent with the observed effect. As described in detail in section 5.3.4, taking account of the end state comfort effect (see Rosenbaum et al., 1990) allows a coherent explanation of the results to be made. The interpretation hinges on the fact the way inverted objects of the tall cylindrical type, originally simply referred to as clockwise compatible, are grasped, is sensitive to the final position of the wrist. The details of the explanation will not be reiterated here. If one accepts that interpretation it implies that more than the kind of low level affordances (those termed micro affordances in section 4.2.1) can be activated by viewing an object. In Experiments 3 and 4 higher level affordances, based on the function of the object during normal usage, were not confounded with the lower level affordances based on the structural properties of the object. The compatibility of an object for being reached for, and grasped, by a particular hand is essentially immune to the purposes to which the object might subsequently be put. The import of this result for the action potentiation account is discussed in a later section.

Wrist rotation cued by tone.

Experiments 6a and 6b examined the wrist rotation component of prehension without using object inversion as the response cue. In order to achieve this responses were cued by a high or low pitched tone stimulus and the experiment was set up under the guise of a recognition memory task. With objects always in their upright position no confounding was present between the low level affordances affecting the direction of wrist rotation used to grasp them and the object types. Clockwise compatible objects always would require a clockwise wrist rotation to grasp them and anticlockwise compatible object an anti-clockwise rotation. In Experiment 6a the response signal was given at the instant the light illuminating the object was turned off. No compatibility effect of object type was observed although there was an interaction between this and mapping. In the mapping condition in which the low tone demanded clockwise wrist rotation responses a compatibility effect was found, a result having a similar pattern in Experiment 6b. In the discussion to Experiment 6a it was suggested that a possible reason for the lack of an effect in this experiment was the fact that the object was no longer in view at the time that responses were executed. The account of action potentiation put forward in this thesis proposes that actions are potentiated by virtue of the way visual objects are represented within the dorsal visuomotor pathway. The nature of the representations used in this pathway tend to be highly transient and rapidly updated, allowing for rapid readjustment of actions in the face of continually changing visual input (Goodale & Milner, 1992; Milner & Goodale, 1993). A consequence of this is that, in Experiment 6a, the potentiated action and its constituent components may be subject to rapid decay after object illumination has ended. It was expected that some residual activation would remain but this may have decayed rapidly enough to prevent a serious effect on response latencies. The notion of decay is important here. As mentioned previously the idea that any automatically activated components of action may decay rapidly after stimulus onset, but *before* stimulus offset is as yet an empirical question that remains to be answered. There is a body of evidence from time course studies of the Simon effect that the automatically activated location code is subject to rapid decay (e.g., Hommel, 1994a; 1994b). The account of action potentiation, however, assumes that the actions an object affords are activated as part of its representation. As such there is no reason to assume that this activation does decay whilst the object remains in view. What is probably more important is the change in visual input as the object ceases to be illuminated. This is not simply a cessation of the visual object but a replacement by a new visual input - in this case the reflective screen. Whether or not action components are subject to decay they will, in these circumstances, be subject to rapid updating and replacement by the new visual input. In order to counter this possibility Experiment 6b repeated Experiment 6a but with the tone cue occurring during object exposure. Under these conditions there was a significant object type by response compatibility effect although this was restricted to the clockwise compatible objects. There was also no three-way interaction between this compatibility effect and mapping. The speed with which wrist rotation responses are made to a tone stimulus is significantly affected by the wrist rotation compatibility of the object that is being attended to at the time the response is made. The finding is more remarkable in as much as no object feature was being used to determine the response. The experiments in which no object property was being used for response determination are probably as ecologically valid a method of testing the action potentiation hypothesis as is possible. They amount to a reasonable experimental approximation of what takes place when we simply view objects without any pre-formed intention to make an action toward them. The final experiment using this methodology examined the last major component of prehension, grasp type selection.

7.2.3. Grasp type and object compatibility

The final experiment examined the effect of objects compatible with either precision or power grips if they were to be grasped. From the recent work by Klatzky et al. (1995) it is established that grip selection takes place before movement onset during goal directed reaches. This study aimed to extend the previous experiments by showing that this third major component of prehension movements could be potentiated without the object being the goal of prehensile action. The method was identical to Experiment 6b and the results even clearer. When subjects made either a precision grip or power grip response whilst viewing an object compatible with one of the two grip types, their response times were significantly affected by the irrelevant compatibility relation. This was mainly the case for the power compatible objects where making a power grip response in the presence of a hammer, for example, was significantly faster than making a precision grip response. Experiment 7 again provides quite striking evidence in favour of action potentiation. Simply viewing an object that would require either a precision or power grip to pick it up significantly influence responses that effectively mimicked one of those grasp types. As mentioned in the discussion of Experiment 7 the results of the last three experiments were complicated by the existence of three-way interactions between the response by object type compatibility effect and the mapping condition subjects were assigned to. In Experiment 6b this interaction was not significant and the straightforward action compatibility effect was the principle finding. However, even there, whilst not significant the pattern of means showed a very similar form to that observed in Experiments 6a and 7. Furthermore, the results of the combined ANOVA on Experiments 6a and 6b confirm the importance of this three-way interaction across the experiments. An explanation was offered to account for this effect although it remains purely conjectural. It must be stressed that the existence of this effect does not drastically modify the evidence for action potentiation, it suggests though, that the effects produced by the action compatibility of the objects is sensitive to as yet unexplained featured of the task.

The major import of the experiments can be stated quite simply. Their aim was to establish that action potentiation does indeed take place when an object is viewed without being the goal of an action. Three major components of one of the most fundamental visually controlled actions were investigated in an experimental paradigm in which the action relevant properties of visual objects, and the responses executed by subjects, were never made explicit. In each case the object-action relation proved to have a significant influence on the speed with which responses were executed. The data provide the first evidence to show that the actions afforded by an object play a significant part in its visual representation. The story is not without complications and certain gaps in explanations but it serves its primary purpose of establishing action potentiation as a serious phenomena that deserves thorough investigation.

7.3. Consequences for Stimulus response compatibility

The series of experiments has some important consequences for SRC. The paradigm is a useful one for investigating object-response relations when they are both irrelevant (as was the case in the experiments reported here) and relevant to response determination. With a few notable exceptions action system effects have been consistently overlooked in the SRC literature. The costs and benefits associated with particular SRC tasks have been attributed to high level rule based processes (Hasbroucq & Guiard, 1990). Of course at some level high level rule based decision processes have to take place - this is the requirement that subjects make responses based on an arbitrary mapping rule. Within the most abstract SRC arrangements very little else takes place - the stimuli are such that they serve as arbitrary premises to a rule based decision: press the right key to the green square, and so on. Worse still the responses themselves are often characterised as mere signs themselves, that is as green or red, thus making the *response* compatibility relation purely symbolic. As Michaels and Stins (1997) emphatically point out :

> "What does it mean to charcterise a response as green? A response code, one would think, should bear some relation to the motor system (forces, impulses, muscles, coordinative structures, paths, trajectories, stiffnesses- *something* that bears some relation to variables that emerge in accounts of movement coordination and control). We submit that the idea that a characteristic of a response is that it is green represents a serious conceptual muddle between what is a stimulus and what is a response." (Michaels & Stins, 1997, p.344).

Consequently any effects that surface from such arrangements cannot be expected to reflect the nature of the visuomotor system. This is acceptable if the goals of SRC are limited to understanding the nature of high level symbolic compatibility relations but, as discussed at the end of Chapter 3, the generalisation of the explanations to more ecologically valid domains is not justified. As Michaels & Stins (1996) point out cognitive codes can always be postulated to exist in order to explain compatibility relations in action relevant environments. This does not entail that they are actually formed, or even if they are generated, that they are responsible for all the compatibility effects observed. The experiments carried out in this work go some way toward establishing a paradigm in which the existence of abstract stimulus codes is minimised, if not eradicated altogether. The relation between perception and action was exploited to this end. Responses can be chosen which not only reflect a meaningful action but also vary along a binary dimension. Likewise object properties were chosen so that they afforded one or other of the binary actions. However the object properties that determined these affordances were not at the same time binary *perceptual* properties. Because of this, the likelihood of the stimuli themselves forming binary stimulus codes is greatly diminished. This is an advantage of using collections of real objects as stimuli. To be sure this also results in experimental data which contains more noise than would be found with abstract displays but the advantages, both in terms of minimising abstract coding and in terms of ecological validity, outweigh this. The results of Experiment 4 attest to the fact that the use of a collection of natural objects with an action relevant property that does vary on a binary left-right dimension does not at the same time result in simple left-right stimulus codes. The binary properties that emerge are consequence of the stimulus effects on the action system.

In as much as the Experiments involved the influence of an *irrelevant* property on response times they formed a natural extension of the Simon paradigm. As stated before only a few studies have explicitly aimed at understanding *why* the spatial codes responsible for the classic Simon experiments are formed at all. The few studies that have undertaken this have all pointed to the importance of attentional processes in their formation. This finding alone makes the proposal that all SRC phenomena are attributable to abstract cognitive coding implausible. Attentional processes, among other things, can be viewed as the first stage in any visuomotor sequence. When the stimuli afford nothing other than attention shifts this is the point where action system effects end. Coloured, abstract stimuli, after all, do not afford actions other than shifts in attention. It is not therefore, as great a leap as it might at first seem to go one step further and argue that affordances over and above attentional orienting are just as much *automatically* activated by the visual properties of objects. The experimental work that makes up the body of this thesis provides evidence that this is indeed the case.

7.4. Implications for visual representation and action.

The potentiation of actions by visual objects has important implications for theories of visual representation in general. What it makes clear is that visual objects are not represented in isolation from the body that is doing the representing. This does not contradict work that has been done on recognition. Undoubtedly there are classes of visual representations in which the object-body relation is of little consequence, where instead, descriptions of visual objects have as their primary purpose the facilitation of unambiguous identification. What is fairly clear from the neurosciences, however, is that multiple representations are the rule rather than the exception. At the same time as viewer invariant object properties are being extracted in the ventral pathway so too are action sensitive representations being formed in the dorsal system. Many cells in the PPC are activated as much when an object is simply attended, as when an action is directed toward it (Stein, 1992). The role of the dorsal system in controlling attention and visuomotor behaviour (and in particular reaching behaviour) is well established. There is, though, little agreement on the precise nature of the distinction between dorsal and ventral processing. As we saw in chapter 2 the distinction has been framed according to many different viewpoints including 'what' versus 'where' (Ungerleider & Mishkin, 1982), 'perception' versus 'action' (Goodale & Milner, 1991), 'near visual field processing' versus 'far processing' (Previc, 1990). No doubt disagreement will remain for many years, over the details of the two systems and the degree of integration between them. Nevertheless the general perspective that action relevant processing predominates in the dorsal system receives considerable support. What the experiments presented here contribute concerns the role of intentions and goal formation in the representation of action parameters. They suggest that the differences in the kinds of representations operating in the two systems go beyond criteria such as the reference frames used. In previous accounts of the processing differences between the two pathways the emphasis has always been on the nature of the representations used *with reference to the information they make explicit for various future tasks*. Such representations can be regarded as visual descriptions that make available information in a suitable format for subsequent computations to be performed. In the case of dorsal processing this includes the broad suggestion that some sort of viewer centred description is formed, as this preserves the relation between the effector systems of the viewer and the object. This description is still, however, entirely visual in as much as any motor system involvement a) arises only after the object has become an explicit goal for an action and b) is generated from scratch by operations that translate visuospatial properties to the motor commands necessary to engage them. Despite the evidence for the large amount of integration between the visual and motor systems the process of acting on a visual input is seen very much as computations performed *on* a visual description. This fosters the view that the motor system's role in visually guided behaviour is essentially that of 'reading' the co-ordinates of a visual description and translating them into motor output.

There is no sense in which the motor system itself is directly involved in the representation of the object in the first place. This separation is, in many ways, a natural consequence of the view that the motor involvement is postponed until specific action goals have been formed. The results of the experiments reported here, however, allow the suggestion to be made that motor involvement takes place much earlier, and, indeed, that the motor system is directly involved in the representation of the object. An intention to perform a particular action results in the selection and elaboration of already existing motor patterns, rather than in their computation *de novo* - a process akin to that proposed for eye movements by Goldberg & Seagraves (1987).

The extent to which higher level actions can be potentiated remains a matter for further investigation. Any visuomotor transformation involves a learning process. Performing a successful reaching movement requires learning the correct motor commands to bring the hand to the object. As pointed out earlier, many of these commands[2] require constant updating, and therefore relearning, as the muscle plant changes (from wear and tear as well as from growth or injury). Higher level actions that take account of object function also involve learning an association between the object and the action that serves its function. Associations between function based actions and the visual object that they relate to no doubt build up over the organisms life history. Whether such actions, themselves, can be potentiated merely by viewing an object remains an open question. The results of Experiment 5 provide some preliminary evidence that this might be the case. However, even if higher level actions are potentiated, it should not be assumed that this potentiation has the same representational basis as that concerning lower level visual object

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[2] Not all the commands are likely to require constant updating as many motor system codes specify the position, for instance, of a target in relatively abstract, kinematic, terms. This level of coding is relatively independent of the actual muscle commands necessary to implement a particular trajectory (see chapter 2).

properties. It may be the case that viewing a pen primes the action of writing. In the neuropsychological studies of Riddoch and colleagues (Riddoch & Humphreys, 1987, Riddoch et al., 1989, Pilgrim & Humphreys, 1991) and the behavioural ones of Rumiati & Humphreys (1996), evidence was obtained for a direct link between visual object descriptions and the actions that perform the function of the objects. This implies that over an individual's history vision-action associations are developed that do not depend on the mediation of semantic knowledge. Thus the function of the object does not need to be explicitly accessed in order for the appropriate action to be accessed, despite the fact that the latter depends on object function. This notion is, however, very different from the account of action potentiation put forward in this thesis, and serves to illustrate an important difference between the potentiation of higher and lower level actions. Perhaps most important of all is the fact that in the gesturing studies subjects were all explicitly required to make an action, thus ruling out the possibility of finding evidence for potentiation in the absence of an action goal. As such the studies do not say anything about motor system involvement in visual representation. This is the major difference between these studies and those presented in chapters 4-6. High level actions may be primed by the object they are associated with, in as much as they make the action more likely, but this is not priming of the same type as that proposed in the action potentiation account. In the latter components of action are primed because they are an integral part of the representation of the object. This is a very different notion from making an action more likely from its association with the object. It has to do with visual representation *per se* rather than associations between the represented object and a commonly performed action, however direct such links may be.

7.5. Proposals for further investigation

Many unresolved questions about action potentiation remain to be investigated. The exact time course of the potentiated components of action remain to be determined. It is not clear whether activation decays over time as deliberate task constraints take over processing, as is the case with the effect of irrelevant location codes in the Simon effect. In as much as action potentiation, as it has been put forward here, involves the motor system in the representation of visual object properties it can be hypothesised that such potentiation will not decay over time whilst the object remains in view. Its effects, however, may be drastically diminished with increasing delay between the time at which the correct response has been determined and its actual execution, as this allows the motor system to be fully controlled by the program for making the correct response. Another line of investigation is needed to determine precisely where along the visuomotor continuum potentiation stops. A central question here, and one that relates to the high-low level distinction above, is the extent to which the motor patterns activated are mainly restricted to kinematic as opposed to dynamic codes (see e.g., Alexander & Crutcher, 1990a). Visuomotor learning mechanisms that constantly update the motor commands necessary to bring about an accurate movement may be chiefly restricted to dynamic codes, in as much as these are affected by external load conditions, and presumably, therefore, changes in the muscle plant. These codes may only be activated once an object has been selected as the goal of an action, whereas the kinematic codes which specify motor commands at more abstract levels may play the central role in the motor component of the object representation. The distinction between kinematic and dynamic motor codes may prove to have considerable relevance in understanding the extent of motor system involvement in the absence of action goals.

More experimental work is needed to gain a thorough understanding of the effects of object distance on the potentiation of components of reaching and grasping. A preliminary investigation was attempted in Experiment 2 but failed to establish any effect of object distance. The evidence for separate attentional systems governing functionally significant parts of space (Rizzolatti et al., 1995) suggests the possibility that potentiation may fall off rapidly as object distance is increased beyond the reaching space. It may be the case, however, that considerable potentiation remains regardless of object distance on account of the intrinsic object properties that remain unaltered with changes in distance. A full understanding of the effects of an object's location, with reference to the functional regions of space surrounding the viewer, would do much to clarify the precise level at which action potentiation occurs. This question could also be addressed by having subjects make their responses when the affordance was not directly possible. For example, the experiments could be repeated with an obstruction between the responding hands and the objects, whilst making sure that the view of the objects was not impeded.

Another possible method of distinguishing between the influence of high level knowledge about object functions and their more immediate low level affordances would be to use stimuli whose perceptual size was distorted. For instance precision - power grip responses could be examined when the viewed objects' actual size was in conflict with their customary size. The immediate affordance for grasping with a particular grip type, based on the objects structural properties, would then be opposed to the grasp type suggested from semantic information about the object.

The role of attention, and the possible interference effects of distractor objects on potentiation, also needs to be fully investigated. All of the studies in this thesis involved the perception of a single object. The presence of distractor objects that share none, some or all of the component affordances of the target object could provide valuable information about the role of attention in action potentiation and help to determine the extent to which multiple affordances can be represented.

Concluding Remarks

The experimental work reported in this thesis provides important preliminary evidence for a view of visual representation which is fundamentally different from traditional approaches. Perception is not isolated from action - the two are integrated to a greater extent than was previously envisaged. When we use vision to extract information about the world and the objects within it we use it in conjunction with the motor systems that depend on vision. The involvement of the motor system allows action relevant object properties to be represented directly by the systems for which that information is potentially relevant. The precise extent of motor involvement is not yet determined but the evidence is sufficient to suggest that when we perform a goal directed action the motor commands that are generated are not generated from scratch. Reaching out to grasp an object involves the elaboration of visuomotor patterns already activated by the presence of the object, patterns that already specify significant components of the action. Action potentiation is a special kind of priming. It is not priming in the sense of making an action more likely given the presence of a visual object (although this may also be take place). Rather the priming of components of action arises because at a fundamental level these components are an intrinsic part of the representation of the object. Whether or not an action is actually to be executed, the motor system plays a central role in building a model of the environment and its physical relation to the observer.

8. APPENDIX 1: Statistical analyses for Experiments 1 & 2.

8.1. Procedure for the calculation of F*min*.

If F_1= the F ratio for the effect by subjects with n and n_1 degrees of freedom and F_2 the F ratio for the effect by objects with n and n_2 degrees of freedom

then $F_{min}\,(n, j)=(F_1 * F_2) / (F_1+F_2)$, and the degrees of freedom, j, the nearest integer to: $(F_1+F_2)^2 / (F_1^2/n_2 + F_2^2/n_1)$.

8.2. Statistical analyses for Experiment 1.

8.2.1. Table of means, standard deviations and *% errors* for Experiment 1 by conditions.

	Mapping			
	RH_High		LH_High	
	Response		Response	
Orientation	Right	Left	Right	Left
Right	424.61	469.52	501.51	523.41
	64.88	77.87	62.78	66.64
	2.33	*2.00*	*3.33*	*3.67*
Left	451.30	475.76	541.54	497.01
	75.65	70.29	71.21	55.32
	2.67	*4.33*	*1.33*	*2.33*

8.2.2. Analysis of variance tables for the analyses by subjects.

i). ANOVA table on subject means computed after removing Response times more than 2 standard deviation from overall subject means.

Source	DF	SS	MS	F	P value
Mapping	1	73369	73369	4.72	0.043
Response	1	2731	2731	2.23	0.153
Orientation	1	2708	2708	8.91	0.008
Map*Resp.	1	10581	10581	8.65	0.009
Map.*Ort.	1	466	466	1.53	0.232
Resp*Ort.	1	9434	9434	5.70	0.028
Map.*Resp*Ort.	1	2643	2643	1.60	0.223
Subject(Map.)	18	279742	15541	9.38	0.000
Resp*Subject(Map.)	18	22022	1223	0.74	0.736
Ort.*Subject(Map.)	18	5468	304	0.18	1.000
Error	18	29813	1656		
Total	79	438975			

ii) ANOVA Table on mean median response times

Source	DF	SS	MS	F	P value
Mapping	1	196862	196862	4.89	0.040
Response	1	5007	5007	4.47	0.049
Orientation	1	3683	3683	1.86	0.189
Map.*Resp.	1	11609	11609	10.37	0.005
Map.*Ort.	1	6	6	0.00	0.955
Resp.*Ort.	1	7095	7095	6.96	0.017
Map.*Resp.*Ort.	1	1609	1609	1.58	0.225
Subject(Map)	18	724124	40229	39.48	0.000
Ort.*Subject(Map.)	18	35622	1979	1.94	0.084
Resp.*Subject(Map.)	18	20149	1119	1.10	0.422
Error	18	18343	1019		
Total	79	1024111			

iii). ANOVA table on mean LOG (RT).

Source	DF	SS	MS	F	P value
Mapping	1	0.827122	0.827122	5.88	0.026
Response	1	0.029592	0.029592	5.55	0.030
Orientation	1	0.015076	0.015076	6.99	0.016
Map.*Resp.	1	0.060849	0.060849	11.41	0.003
Map.*Ort.	1	0.000556	0.000556	0.26	0.618
Resp.*Ort.	1	0.021726	0.021726	6.92	0.017
Map.*Resp.*Ort.	1	0.004455	0.004455	1.42	0.249
Subject(Map.)	18	2.531941	0.140663	44.81	0.000
Ort.*Subject(Map.)	18	0.038802	0.002156	0.69	0.784
Resp.*Subject(Map.)	18	0.096019	0.005334	1.70	0.135
Error	18	0.056506	0.003139		
Total	79	3.682646			

8.2.3. ANOVA table for the materials Analysis.

Response times more than 2 standard deviations from subject overall means removed.

Source	DF	SS	MS	F	P value
Mapping	1	61901.3	61901.3	127.36	0.000
Response	1	2132.8	2132.8	4.40	0.065
Orientation	1	2962.2	2962.2	7.36	0.024
Object	9	4919.1	546.6	3.11	0.053
Map.*Resp.	1	10168.7	10168.7	26.88	0.000
Map.*Ort.	1	609.0	609.0	1.50	0.252
Map.*Object	9	4374.5	486.1	2.76	0.073
Resp.*Ort.	1	6195.7	6195.7	19.38	0.002
Resp.*Object	9	4358.3	484.3	2.75	0.074
Ort.*Object	9	3622.8	402.5	2.29	0.117
Map.*Resp.*Ort.	1	908.7	908.7	5.16	0.049
Map.*Resp.*Object	9	3404.5	378.3	2.15	0.135
Map.*Ort.*Object	9	3657.4	406.4	2.31	0.114
Resp.*Ort.*Object	9	2876.9	319.7	1.82	0.194
Error	9	1583.6	176.0		
Total	79	113675.5			

8.2.4. ANOVA table for the analysis of Subject error rates.

Source	DF	SS	MS	F	P value
Mapping	1	0.56	0.56	0.03	0.858
Response	1	8.89	8.89	0.84	0.372
Orientation	1	0.56	0.56	0.06	0.815
Map.*Resp.	1	0.00	0.00	0.00	1.000
Map.*Ort.	1	45.00	45.00	4.58	0.046
Resp.*Ort.	1	8.89	8.89	0.69	0.418
Map.*Resp.*Ort.	1	2.22	2.22	0.17	0.684
Subject(Map.)	18	305.56	16.98	1.31	0.287
Resp.*Subject(Map.	18	191.11	10.62	0.82	0.662
Ort.*Subject(Map.)	18	176.67	9.81	0.76	0.719
Error	18	233.33	12.96		
Total	79	972.78			

8.3. Statistical analyses for Experiment 2.

8.3.1. Table of means, standard deviations and *% errors* for Experiment 2 by conditions.

	Mapping			
	RH_High		LH_High	
	Response		Response	
Orientation	Right	Left	Right	Left
Right	510.93	529.76	588.82	579.74
	55.20	59.10	72.01	74.46
	3.66	*3.39*	*4.01*	*4.91*
Left	513.45	535.79	584.31	586.21
	58.35	64.75	68.57	69.51
	2.95	*3.84*	*3.21*	*4.82*

8.3.2. Analysis of Variance tables for the subjects analysis.

i). ANOVA table on subject means computed after removing response times more than 2 standard deviations from subjects overall means.

Source	DF	SS	MS	F	P value
Orientation	1	387	387	1.26	0.272
Response	1	4045	4045	3.40	0.076
Distance	1	467	467	0.17	0.686
Mapping	1	217286	217286	7.23	0.012
Ort.*Resp.	1	734	734	1.32	0.261
Ort.*Dist.	1	169	169	1.00	0.326
Ort.*Map.	1	152	152	0.49	0.488
Resp.*Dist.	1	293	293	0.80	0.378
Resp.*Map.	1	8183	8183	6.89	0.014
Dist.*Map.	1	361	361	0.13	0.723
Ort.*Resp.*Dist.	1	42	42	0.22	0.645
Ort.*Resp.*Map.	1	196	196	0.35	0.558
Ort.*Dist.*Map.	1	184	184	1.09	0.305
Resp.*Dist.*Map.	1	177	177	0.48	0.492
Ort.*Resp.*Dist.*Map.	1	533	533	2.75	0.109
subject(Map.)	26	781557	30060	154.98	0.000
Ort.*subject(Map.)	26	7994	307	1.59	0.123
Resp.*subject(Map.)	26	30897	1188	6.13	0.000
Dist.*subject(Map.)	26	72794	2800	14.43	0.000
Ort.*Resp.*subject(Map.)	26	14441	555	2.86	0.005
Ort.*Dist.*subject(Map.)	26	4381	168	0.87	0.639
Resp.*Dist.*subject(Map.)	26	9482	365	1.88	0.057
Error	26	5043	194		
Total		223	1159796		

ii). ANOVA table for the analysis on mean Median RT.

Source	DF	SS	MS	F	P value
Orientation	1	9	9	0.03	0.874
Response	1	9356	9356	5.32	0.029
Distance	1	3454	3454	0.76	0.390
Mapping	1	215314	215314	5.55	0.026
Ort.*Resp.	1	1	1	0.00	0.975
Ort.*Dist.	1	641	641	1.58	0.220
Ort.*Map.	1	3	3	0.01	0.923
Resp.*Dist.	1	119	119	0.15	0.702
Resp.*Map.	1	23045	23045	13.09	0.001
Dist.*Map.	1	38	38	0.01	0.928
Ort.*Resp.*Dist.	1	21	21	0.07	0.801
Ort.*Respons*Map.	1	246	246	0.31	0.582
Ort.*Dist.*Map.	1	292	292	0.72	0.404
Resp.*Dist.*Map.	1	536	536	0.68	0.418
Ort.*Resp.*Dist.*Map.	1	26	26	0.08	0.780
Subject(Map.)	26	1009102	38812	118.04	0.000
Ort.*Subject(Map.)	26	9458	364	1.11	0.399
Resp.*Subject(Map.)	26	45760	1760	5.35	0.000
Dist.*Subject(Map.)	26	117573	4522	13.75	0.000
Ort.*Resp.*Subject(Map.)	26	20564	791	2.41	0.015
Ort.*Dist.*Subject(Map.)	26	10566	406	1.24	0.297
Resp.*Dist.*Subject(Map.)	26	20601	792	2.41	0.014
Error	26	8549	329		
Total	223	1495275			

iii). ANOVA table for the analysis on mean LOG (RT).

Source	DF	SS	MS	F	P value
Orientation	1	0.000552	0.000552	0.68	0.416
Response	1	0.016991	0.016991	3.88	0.060
Distance	1	0.013733	0.013733	0.91	0.350
Mapping	1	0.764756	0.764756	5.42	0.028
Ort.*Resp.	1	0.001080	0.001080	0.51	0.480
Ort.*Dist.	1	0.002659	0.002659	3.98	0.057
Ort.*Map.	1	0.000145	0.000145	0.18	0.676
Resp.*Dist.	1	0.000109	0.000109	0.04	0.838
Resp.*Map.	1	0.102249	0.102249	23.34	0.000
Dist.*Map.	1	0.000489	0.000489	0.03	0.859
Ort.*Resp.*Dist.	1	0.000079	0.000079	0.08	0.776
Ort.*Resp.*Map.	1	0.000702	0.000702	0.33	0.568
Ort.*Dist.*Map.	1	0.001594	0.001594	2.39	0.135
Resp.*Dist.*Map.	1	0.000018	0.000018	0.01	0.934
Ort.*Resp.*Dist.*Map.	1	0.000833	0.000833	0.87	0.359
Subject(Map.)	26	3.666374	0.141014	147.96	0.000
Ort.*Subject(Map.)	26	0.020965	0.000806	0.85	0.663
Resp.*Subject(Map.)	26	0.113896	0.004381	4.60	0.000
Dist.*Subject(Map.)	26	0.394059	0.015156	15.90	0.000
Ort.*Resp.*Subject(Map.)	26	0.054705	0.002104	2.21	0.024
Ort.*Dist.*Subject(Map.)	26	0.017367	0.000668	0.70	0.815
Resp.*Dist.*Subject(Map.)	26	0.066287	0.002549	2.68	0.007
Error	26	0.024780	0.000953		
Total	223	5.264419			

8.3.3. ANOVA table for the analysis of materials.

Response times more than 2 standard deviations from subject overall means removed.

Source	DF	SS	MS	F	P value
Object	19	144898.3	7626.2	18.99	0.000
Orientation	1	708.1	708.1	1.79	0.196
Response	1	7230.6	7230.6	10.26	0.005
Distance	1	284.7	284.7	0.43	0.521
Mapping	1	299814.0	299814.0	407.68	0.000
Object*Ort.	19	7506.0	395.1	0.98	0.514
Object*Resp.	19	13394.4	705.0	1.76	0.115
Object*Dist.	19	12652.4	665.9	1.66	0.140
Object*maps	19	13972.9	735.4	1.83	0.098
Ort.*Resp.	1	1091.5	1091.5	4.46	0.048
Ort.*Dist.	1	75.5	75.5	0.18	0.677
Ort.*maps	1	89.5	89.5	0.23	0.638
Resp.*Dist.	1	395.5	395.5	1.00	0.330
Resp.*maps	1	11927.7	11927.7	17.68	0.000
Dist.*maps	1	823.6	823.6	1.71	0.207
Object*Ort.*Resp.	19	4648.8	244.7	0.61	0.855
Object*Ort.*Dist.	19	7988.8	420.5	1.05	0.461
Object*Ort.*maps	19	7424.7	390.8	0.97	0.523
Object*Resp.*Dist.	19	7515.6	395.6	0.99	0.513
Object*Resp.*maps	19	12814.7	674.5	1.68	0.134
Object*Dist.*maps	19	9165.5	482.4	1.20	0.347
Ort.*Resp.*Dist.	1	5.5	5.5	0.02	0.878
Ort.*Resp.*maps	1	231.4	231.4	0.63	0.439
Ort.*Dist.*maps	1	176.6	176.6	0.86	0.366
Resp.*Dist.*maps	1	92.6	92.6	0.12	0.734
Object*Ort.*Resp.*Dist.	19	4328.1	227.8	0.57	0.887
Object*Ort.*Resp.*maps	19	7028.0	369.9	0.92	0.570
Object*Ort.*Dist.*maps	19	3917.1	206.2	0.51	0.922
Object*Resp.*Dist.*maps	19	14755.2	776.6	1.93	0.080
Ort.*Resp.*Dist.*maps	1	718.5	718.5	1.79	0.197
Error	19	7629.5	401.6		
Total	319	603305.1			

8.3.4. ANOVA table for the error rate analysis.

Source	DF	SS	MS	F	P value
Orientation	1	4.715	4.715	0.44	0.514
Response	1	34.180	34.180	1.95	0.174
Mapping	1	34.180	34.180	1.13	0.298
Distance	1	0.698	0.698	0.06	0.801
Ort.*Resp.	1	12.305	12.305	1.08	0.308
Ort.*Map.	1	1.367	1.367	0.13	0.725
Ort.*Dist.	1	4.715	4.715	0.40	0.531
Resp.*Map.	1	12.305	12.305	0.70	0.410
Resp.*Dist.	1	4.715	4.715	0.53	0.472
Map.*Dist.	1	3.376	3.376	0.31	0.580
Ort.*Resp.*Map.	1	0.698	0.698	0.06	0.806
Ort.*Resp.*Dist.	1	2.260	2.260	0.32	0.574
Ort.*Map.*Dist.	1	0.251	0.251	0.02	0.885
Resp.*Map.*Dist.	1	1.367	1.367	0.15	0.698
Ort.*Resp.*Map.*Dist.	1	3.376	3.376	0.48	0.492
Subject(Map.)	26	787.779	30.299	4.35	0.000
Ort.*Subject(Map.)	26	280.636	10.794	1.55	0.135
Resp.*Subject(Map.)	26	455.859	17.533	2.52	0.011
Dist.*Subject(Map.)	26	279.520	10.751	1.54	0.137
Ort.*Resp.*Subject(Map.)	26	295.592	11.369	1.63	0.109
Ort.*Dist.*Subject(Map.)	26	303.627	11.678	1.68	0.097
Resp.*Dist.*Subject(Map.)	26	230.636	8.871	1.27	0.271
Error	26	181.083	6.965		
Total	223	2935.240			

9. APPENDIX 2: Statistical analyses for Experiments 3 & 4.

9.1. Statistical analyses and summary tables for Experiment 3.

9.1.1. Table of means, standard deviations and *% errors* for Experiment 3 by conditions.

	Mapping			
	RH_UP		LH_UP	
	Response		Response	
Orientation	Right	Left	Right	Left
Right	596.08 79.69 *3.7110*	630.09 91.59 *6.0215*	649.79 118.95 *5.8109*	644.31 120.56 *6.4604*
Left	609.42 91.43 *4.9260*	615.21 85.99 *3.8353*	660.21 112.70 *7.2059*	635.97 118.71 *3.7958*

9.1.2. Analysis of Variance tables for the analyses by subjects.

i). Means computed after removing reaction times more than 2 standard deviations from subjects overall means.

Source	DF	SS	MS	F	P value
Subject	27	1943143	71968	139.22	0.000
Orientation	1	1	1	0.00	0.964
Mapping	1	68100	68100	7.54	0.011
Response	1	355	355	0.32	0.574
Subject*Ort.	27	12199	452	0.87	0.636
Subject*Map.	27	243703	9026	17.46	0.000
Subject*Resp.	27	29617	1097	2.12	0.028
Ort.*Map.	1	46	46	0.07	0.793
Ort.*Resp.	1	7727	7727	19.13	0.000
Map.*Resp.	1	16919	16919	9.12	0.005
Subject*Ort.*Map.	27	17634	653	1.26	0.274
Subject*Ort.*Resp.	27	10908	404	0.78	0.737
Subject*Map.*Resp.	27	50073	1855	3.59	0.001
Ort.*Map.*Resp.	1	312	312	0.60	0.444
Error	27	13958	517		
Total	223	2414697			

ii). ANOVA table for the analysis on median RT.

Source	DF	SS	MS	F	P value
Subject	27	1624591	60170	65.30	0.000
Orientation	1	619	619	0.58	0.454
Mapping	1	108909	108909	9.14	0.005
Response	1	629	629	0.39	0.537
Subject*Ort.	27	28922	1071	1.16	0.349
Subject*Map.	27	321702	11915	12.93	0.000
Subject*Resp.	27	43426	1608	1.75	0.077
Ort.*Map.	1	114	114	0.11	0.743
Ort.*Resp.	1	9293	9293	9.14	0.005
Map.*Resp.	1	34148	34148	12.03	0.002
Subject*Ort.*Map.	27	28152	1043	1.13	0.375
Subject*Ort.*Resp.	27	27449	1017	1.10	0.400
Subject*Map.*Resp.	27	76666	2839	3.08	0.002
Ort.*Map.*Resp.	1	458	458	0.50	0.487
Error	27	24878	921		
Total	223	2329957			

iii). ANOVA table for the analysis on LOG (RT).

Source	DF	SS	MS	F	P value
Subject	27	4.491680	0.166359	104.50	0.000
Orientation	1	0.003568	0.003568	2.02	0.166
Mapping	1	0.213431	0.213431	7.25	0.012
Response	1	0.000024	0.000024	0.01	0.933
Subject*Ort.	27	0.047582	0.001762	1.11	0.397
Subject*Map.	27	0.794723	0.029434	18.49	0.000
Subject*Resp.	27	0.089398	0.003311	2.08	0.031
Ort.*Map.	1	0.000139	0.000139	0.11	0.743
Ort.*Resp.	1	0.015965	0.015965	10.34	0.003
Map.*Resp.	1	0.070803	0.070803	14.35	0.001
Subject*Ort.*Map.	27	0.034140	0.001264	0.79	0.723
Subject*Ort.*Resp.	27	0.041670	0.001543	0.97	0.532
Subject*Map.*Resp.	27	0.133230	0.004934	3.10	0.002
Ort.*Map.*Resp.	1	0.000802	0.000802	0.50	0.484
Error	27	0.042984	0.001592		
Total	223	5.980139			

9.1.3. ANOVA table for the analysis of materials.

Response times more than 2 standard deviations from subject overall means discarded.

Source	DF	SS	MS	F	P value
Object	21	373178	17770	17.61	0.000
Orientation	1	15	15	0.02	0.902
Mapping	1	50152	50152	61.45	0.000
Response	1	16	16	0.03	0.857
Object*Ort.	21	20498	976	0.97	0.530
Object*Map.	21	17140	816	0.81	0.685
Object*Resp.	21	10279	489	0.48	0.948
Ort.*Map.	1	117	117	0.19	0.665
Ort.*Resp.	1	9254	9254	27.74	0.000
Map.*Resp.	1	11786	11786	5.21	0.033
Object*Ort.*Map.	21	12742	607	0.60	0.874
Object*Ort.*Resp.	21	7005	334	0.33	0.993
Object*Map.*Resp.	21	47520	2263	2.24	0.036
Ort.*Map.*Resp.	1	761	761	0.75	0.395
Error	21	21197	1009		
Total	175	581660			

9.1.4. ANOVA table for the analysis of subject error rates.

Source	DF	SS	MS	F	P value
Subject	27	1444.00	53.48	5.22	0.000
Orientation	1	17.57	17.57	3.16	0.087
Mapping	1	79.94	79.94	3.92	0.058
Response	1	8.31	8.31	0.49	0.490
Subject*Ort.	27	150.00	5.56	0.54	0.941
Subject*Map.	27	550.55	20.39	1.99	0.040
Subject*Resp.	27	458.59	16.98	1.66	0.098
Ort.*Map.	1	0.31	0.31	0.04	0.850
Ort.*Resp.	1	194.82	194.82	14.52	0.001
Map.*Resp.	1	55.45	55.45	2.94	0.098
Subject*Ort.*Map.	27	231.03	8.56	0.83	0.679
Subject*Ort.*Resp.	27	362.18	13.41	1.31	0.245
Subject*Map.*Resp.	27	509.14	18.86	1.84	0.060
Ort.*Map.*Resp.	1	1.52	1.52	0.15	0.703
Error	27	276.77	10.25		
Total	223	4340.20			

9.2. Statistical analyses and summary tables for Experiment 4.

9.2.1. Table of means, standard deviations and % *errors* for Experiment 4 by conditions.

	Mapping			
	RF_UP		LF_UP	
	Response		Response	
Orientation	Right	Left	Right	Left
Right	609.95	623.12	630.87	611.30
	125.11	109.82	115.24	115.94
	3.98	*5.09*	*3.98*	*4.91*
Left	608.73	613.90	625.48	599.86
	124.98	103.51	99.53	90.93
	3.89	*2.69*	*3.98*	*3.52*

9.2.2. Analysis of variance tables for the analyses by subjects.

i). ANOVA table on mean RT after removing response times more than 2 standard deviations from individual subject means.

Source	DF	SS	MS	F	P value
Subject	26	2281389	87746	468.28	0.000
Mapping	1	471	471	0.08	0.784
Response	1	2433	2433	1.55	0.224
Orientation	1	2509	2509	2.05	0.164
Subject*Map.	26	159493	6134	32.74	0.000
Subject*Resp.	26	40806	1569	8.38	0.000
Subject*Ort.	26	31789	1223	6.53	0.000
Map.*Resp.	1	13623	13623	15.53	0.001
Map.*Ort.	1	137	137	0.17	0.681
Resp.*Ort.	1	668	668	1.61	0.215
Subject*Map.*Resp.	26	22812	877	4.68	0.000
Subject*Map.*Ort.	26	20622	793	4.23	0.000
Subject*Resp.*Ort.	26	10762	414	2.21	0.024
Map.*Resp.*Ort.	1	13	13	0.07	0.795
Error	26	4872	187		
Total	215	2592400			

ii). ANOVA table for the analysis on mean Median RT.

Source	DF	SS	MS	F	P value
Subject	26	2028424	78016	134.29	0.000
Mapping	1	588	588	0.08	0.784
Response	1	2116	2116	1.17	0.290
Orientation	1	7510	7510	4.56	0.042
Subject*Map.	26	198769	7645	13.16	0.000
Subject*Resp.	26	47184	1815	3.12	0.003
Subject*Ort.	26	42772	1645	2.83	0.005
Map.*Resp.	1	25411	25411	17.50	0.000
Map.*Ort.	1	48	48	0.03	0.871
Resp.*Ort.	1	3119	3119	5.18	0.031
Subject*Map.*Resp.	26	37756	1452	2.50	0.011
Subject*Map.*Ort.	26	46636	1794	3.09	0.003
Subject*Resp.*Ort.	26	15647	602	1.04	0.465
Map.*Resp.*Ort.	1	515	515	0.89	0.355
Error	26	15105	581		
Total	215	2471600			

iii). ANOVA table on for the analysis on mean LOG (RT).

Source	DF	SS	MS	F	P value
Subject	26	5.752983	0.221269	240.11	0.000
Mapping	1	0.000926	0.000926	0.05	0.827
Response	1	0.002151	0.002151	0.85	0.365
Orientation	1	0.006237	0.006237	2.65	0.116
Subject*Map.	26	0.493488	0.018980	20.60	0.000
Subject*Resp.	26	0.065910	0.002535	2.75	0.006
Subject*Ort.	26	0.061154	0.002352	2.55	0.010
Map.*Resp.	1	0.068471	0.068471	20.07	0.000
Map.*Ort.	1	0.000021	0.000021	0.01	0.924
Resp.*Ort.	1	0.004271	0.004271	3.24	0.083
Subject*Map.*Resp.	26	0.088705	0.003412	3.70	0.001
Subject*Map.*Ort.	26	0.058289	0.002242	2.43	0.014
Subject*Resp.*Ort.	26	0.034235	0.001317	1.43	0.184
Map.*Resp.*Ort.	1	0.000299	0.000299	0.32	0.574
Error	26	0.023959	0.000922		
Total	215	6.661097			

9.2.3. ANOVA table for the analysis of materials.

Source	DF	SS	MS	F	P value
Object	19	334275.5	17593.4	21.55	0.000
Mapping	1	254.4	254.4	0.83	0.375
Response	1	1288.7	1288.7	4.24	0.053
Orientation	1	2008.1	2008.1	3.17	0.091
Object*Map.	19	5847.5	307.8	0.38	0.980
Object*Resp.	19	5775.9	304.0	0.37	0.981
Object*Ort.	19	12023.6	632.8	0.77	0.708
Map.*Resp.	1	8102.8	8102.8	5.22	0.034
Map.*Ort.	1	12.8	12.8	0.05	0.828
Resp.*Ort.	1	212.3	212.3	0.31	0.583
Object*Map.*Resp.	19	29487.8	1552.0	1.90	0.085
Object*Map.*Ort.	19	5048.4	265.7	0.33	0.991
Object*Resp.*Ort.	19	12897.3	678.8	0.83	0.654
Map.*Resp.*Ort.	1	1.5	1.5	0.00	0.967
Error	19	15514.5	816.6		
Total	159	432751.0			

9.2.4. Analysis of subject error rates.

Source	DF	SS	MS	F	P value
Subject	27	1444.00	53.48	5.22	0.000
Orientation	1	17.57	17.57	3.16	0.087
Mapping	1	79.94	79.94	3.92	0.058
Response	1	8.31	8.31	0.49	0.490
Subject*Ort.	27	150.00	5.56	0.54	0.941
Subject*Map.	27	550.55	20.39	1.99	0.040
Subject*Resp.	27	458.59	16.98	1.66	0.098
Ort.*Map.	1	0.31	0.31	0.04	0.850
Ort.*Resp.	1	194.82	194.82	14.52	0.001
Map.*Resp.	1	55.45	55.45	2.94	0.098
Subject*Ort.*Map.	27	231.03	8.56	0.83	0.679
Subject*Ort.*Resp.	27	362.18	13.41	1.31	0.245
Subject*Map.*Resp.	27	509.14	18.86	1.84	0.060
Ort.*Map.*Resp.	1	1.52	1.52	0.15	0.703
Error	27	276.77	10.25		
Total	223	4340.20			

9.3. Grand ANOVA table on the pooled data from Experiments 3 and 4.

Response times computed after removing reaction times more than 2 standard deviations from individual subject overall means.

Source	DF	SS	MS	F	P value
Orientation	1	1198	1198	1.42	0.239
Mapping	1	36566	36566	4.73	0.034
Response	1	366	366	0.27	0.605
Experiment	1	25645	25645	0.32	0.577
Ort.*Map.	1	26	26	0.04	0.852
Ort.*Resp.	1	6178	6178	14.84	0.000
Ort.*Exp.	1	1312	1312	1.55	0.219
Map.*Resp.	1	28943	28943	20.77	0.000
Map.*Exp.	1	25765	25765	3.34	0.074
Resp.*Exp.	1	2564	2564	1.90	0.174
Ort.*Map.*Resp.	1	143	143	0.40	0.528
Ort.*Map.*Exp.	1	132	132	0.18	0.673
Ort.*Resp.*Exp.	1	1768	1768	4.25	0.044
Map.*Resp.*Exp.	1	26	26	0.02	0.893
Ort.*Map.*Resp.*Exp.	1	47	47	0.13	0.717
Subject(Exp.)	52	4221785	81188	229.82	0.000
Ort.*Subject(Exp.)	52	43987	846	2.39	0.001
Map.*Subject(Exp.)	52	401604	7723	21.86	0.000
Resp.*Subject(Exp.)	52	70025	1347	3.81	0.000
Ort.*Map.*Subject(Exp.)	52	38131	733	2.08	0.005
Ort.*Resp.*Subject(Exp.)	52	21641	416	1.18	0.278
Map.*Resp.*Subject(Exp.)	52	72471	1394	3.95	0.000
Error	52	18370	353		
Total	431	5018693			

10. APPENDIX 3: Statistical analyses for Experiments 5-7.

10.1. Statistical anayses and summary tables for Experiment 5.

10.1.1. Tables of means, standard deviations and *% errors* for Experiment 5 by conditions. Means computed after removing response times more than 2 standard deviations from overall subject means.

	Mapping			
	C_UP		AC_UP	
	Response		Response	
Compatibility	C/wise	AC/wise	C/wise	AC/wise
C/wise	745.67	717.63	798.07	740.05
	122.76	103.22	127.70	113.06
	5.089	*4.196*	*3.125*	*1.607*
AC/wise	829.36	791.86	841.70	806.06
	131.09	102.97	139.03	118.30
	12.411	*10.268*	*7.232*	*3.036*

10.1.2. Analysis of variance tables for the analyses by subjects.

i). ANOVA table on mean RT after removing response times more than 2 standard deviations from individual subject means.

Source	DF	SS	MS	F	P value
Subject	27	2397884	88811	56.99	0.000
Compatibility	1	250565	250565	76.15	0.000
Response	1	88690	88690	34.22	0.000
Mapping	1	35949	35949	2.86	0.102
Subject*Comp.	27	88847	3291	2.11	0.029
Subject*Resp.	27	69973	2592	1.66	0.096
Subject*Map.	27	339387	12570	8.07	0.000
Comp.*Resp.	1	584	584	0.46	0.502
Comp.*Map.	1	8158	8158	5.75	0.024
Resp.*Map.	1	2765	2765	0.63	0.436
Subject*Comp.*Resp.	27	34105	1263	0.81	0.705
Subject*Comp.*Map.	27	38309	1419	0.91	0.595
Subject*Resp.*Map.	27	119437	4424	2.84	0.004
Comp.*Resp.*Map.	1	3550	3550	2.28	0.143
Error	27	42077	1558		
Total	223	3520280			

ii). ANOVA table for the analysis using mean median RT.

Source	DF	SS	MS	F	P value
Subject	27	2286916	84701	39.91	0.000
Compatibility	1	313255	313255	62.09	0.000
Response	1	107801	107801	36.54	0.000
Mapping	1	40781	40781	2.46	0.128
Subject*Comp.	27	136226	5045	2.38	0.014
Subject*Resp.	27	79650	2950	1.39	0.199
Subject*Map.	27	447459	16573	7.81	0.000
Comp.*Resp.	1	12	12	0.01	0.925
Comp.*Map.	1	12057	12057	4.20	0.050
Resp.*Map.	1	3010	3010	0.55	0.466
Subject*Comp.*Resp.	27	34755	1287	0.61	0.900
Subject*Comp.*Map.	27	77449	2868	1.35	0.219
Subject*Resp.*Map.	27	148639	5505	2.59	0.008
Comp.*Resp.*Map.	1	6565	6565	3.09	0.090
Error	27	57299	2122		
Total	223	3751872			

iii). ANOVA table for the analysis using mean LOG (RT).

Source	DF	SS	MS	F	P value
Subject	27	4.346203	0.160970	53.29	0.000
Compatibility	1	0.681671	0.681671	71.56	0.000
Response	1	0.165775	0.165775	33.60	0.000
Mapping	1	0.047265	0.047265	1.60	0.217
Subject*Comp.	27	0.257216	0.009527	3.15	0.002
Subject*Resp.	27	0.133226	0.004934	1.63	0.104
Subject*Map.	27	0.796842	0.029513	9.77	0.000
Comp.*Resp.	1	0.002689	0.002689	1.06	0.313
Comp.*Map.	1	0.015219	0.015219	3.77	0.063
Resp.*Map.	1	0.012973	0.012973	1.57	0.221
Subject*Comp.*Resp.	27	0.068775	0.002547	0.84	0.670
Subject*Comp.*Map.	27	0.108996	0.004037	1.34	0.228
Subject*Resp.*Map.	27	0.222979	0.008258	2.73	0.006
Comp.*Resp.*Map.	1	0.000737	0.000737	0.24	0.625
Error	27	0.081558	0.003021		
Total	223	6.942125			

10.1.3. ANOVA table for the analysis of materials.

Source	DF	SS	MS	F	P value
Compatibility	1	220843	220843	17.31	0.000
Response	1	70375	70375	115.77	0.000
Mapping	1	23120	23120	16.65	0.000
Comp.*Resp.	1	494	494	0.81	0.373
Comp.*Map.	1	8207	8207	5.91	0.020
Resp.*Map.	1	3423	3423	3.31	0.077
Comp.*Resp.*Map.	1	1138	1138	1.10	0.301
Object(Comp.)	38	484842	12759	12.34	0.000
Resp.*Object(Comp.)	38	23101	608	0.59	0.947
Map.*Object(Comp.)	38	52760	1388	1.34	0.184
Error	38	39298	1034		
Total	159	927600			

10.1.4. ANOVA table for the analysis of subject error rates.

Source	DF	SS	MS	F	P value
Subject	27	2875.56	106.50	3.50	0.001
Compatibility	1	1254.02	1254.02	45.67	0.000
Response	1	267.97	267.97	7.22	0.012
Mapping	1	1007.25	1007.25	12.70	0.001
Subject*Comp.	27	741.29	27.46	0.90	0.606
Subject*Resp.	27	1002.34	37.12	1.22	0.306
Subject*Map.	27	2141.18	79.30	2.60	0.008
Comp.*Resp.	1	54.02	54.02	1.90	0.179
Comp.*Map.	1	216.07	216.07	4.59	0.041
Resp.*Map.	1	25.11	25.11	0.96	0.335
Subject*Comp.*Resp.	27	766.29	28.38	0.93	0.572
Subject*Comp.*Map.	27	1269.87	47.03	1.54	0.133
Subject*Resp.*Map.	27	704.58	26.10	0.86	0.655
Comp.*Resp.*Map.	1	7.14	7.14	0.23	0.632
Error	27	822.54	30.46		
Total	223	13155.25			

10.1.5. Table of means standard deviations and error rates for the analysis with object inversion as a factor.

	Response			
	C/Wise		AC/Wise	
	Inversion		Inversion	
Compatibility	Upright	Inverted	Upright	Inverted
C/wise	745.67 122.76 *5.09*	798.07 127.70 *3.13*	740.05 113.06 *1.61*	717.63 103.22 *4.20*
AC/wise	829.36 131.09 *12.41*	841.70 139.03 *7.23*	806.06 118.30 *3.04*	791.86 102.97 *10.27*

10.1.6. ANOVA tables for the analyses with object inversion as a factor.

i). Overall ANOVA table including object inversion.

Means computed after removing reaction times more than 2 standard deviations from overall subject means.

Source	DF	SS	MS	F	P value
Subject	27	2397884	88811	62.59	0.000
Compatibility	1	250565	250565	76.15	0.000
Inversion	1	2765	2765	0.63	0.436
Response	1	88690	88690	34.22	0.000
Subject*Comp.	27	88847	3291	2.32	0.016
Subject*Inv.	27	119437	4424	3.12	0.002
Subject*Resp.	27	69973	2592	1.83	0.062
Comp.*Inv.	1	3550	3550	2.28	0.143
Comp.*Resp.	1	584	584	0.46	0.502
Inv.*Resp.	1	35949	35949	2.86	0.102
Subject*Comp.*Inv.	27	42077	1558	1.10	0.405
Subject*Comp.*Resp.	27	34105	1263	0.89	0.618
Subject*Inv.*Resp.	27	339387	12570	8.86	0.000
Comp.*Inv.*Resp.	1	8158	8158	5.75	0.024
Error	27	38309	1419		
Total	223	3520280			

10.1.7. Simple interaction effects for the analysis with object inversion.

i). ANOVA table for the Clockwise compatible objects.

Source	DF	SS	MS	F	P value
Subject	27	1138275	42158	5.36	0.000
Inversion	1	6291	6291	2.38	0.134
Response	1	51837	51837	24.03	0.000
Subject*Inv.	27	71251	2639	0.34	0.997
Subject*Resp.	27	58251	2157	0.27	0.999
Inv.*Resp.	1	39178	39178	4.98	0.034
Error	27	212305	7863		
Total	111	1577388			

ii). ANOVA table for the Anti-clockwise compatible objects.

Source	DF	SS	MS	F	P value
Subject	27	1348455	49943	8.15	0.000
Inversion	1	25	25	0.01	0.932
Response	1	37437	37437	22.06	0.000
Subject*Inv.	27	90264	3343	0.55	0.939
Subject*Resp.	27	45827	1697	0.28	0.999
Inv.*Resp.	1	4928	4928	0.80	0.378
Error	27	165390	6126		
Total	111	1692327			

10.2. Statistical analyses and summary tables for Experiment 6a.

10.2.1. Table of means, standard deviations and % errors for Experiment 6a by conditions. Response times more than 2 sds from overall subject means excluded.

	Mapping			
	H_C		L_C	
	Response		Response	
Compatibility	C/wise	AC/wise	C/wise	AC/wise
C/wise	386.58	389.51	443.62	454.46
	73.74	63.83	94.68	73.70
	6.43	*7.68*	*4.64*	*4.64*
AC/wise	388.56	397.89	456.52	445.59
	63.97	66.25	91.08	87.84
	3.57	*8.04*	*6.43*	*5.00*

10.2.2. Analysis of variance tables for the subjects analyses.

i). Means computed after removing reaction times more than 2 standard deviations from subject overall means.

Source	DF	SS	MS	F	P value
Compatibility	1	362.8	362.8	0.75	0.394
Response	1	258.9	258.9	0.30	0.591
Mapping	1	98834.9	98834.9	4.39	0.046
Comp.*Resp.	1	412.8	412.8	1.26	0.272
Comp.*Map.	1	70.1	70.1	0.15	0.706
Resp.*Map.	1	266.4	266.4	0.30	0.586
Comp.*Resp.*Map.	1	1389.1	1389.1	4.24	0.050
Subject(Map.)	26	585380.8	22514.6	68.65	0.000
Comp.*Subject(Map.)	26	12541.9	482.4	1.47	0.166
Resp.*Subject(Map.)	26	22757.6	875.3	2.67	0.008
Error	26	8526.7	327.9		
Total	111	730801.9			

ii). Means computed using Median RT.

Source	DF	SS	MS	F	P value
Compatibility	1	153.9	153.9	0.21	0.648
Response	1	980.6	980.6	0.80	0.378
Mapping	1	68745.7	68745.7	3.34	0.079
Comp.*Resp.	1	46.3	46.3	0.08	0.785
Comp.*Map.	1	4.6	4.6	0.01	0.937
Resp.*Map.	1	214.8	214.8	0.18	0.678
Comp.*Resp.*Map.	1	983.6	983.6	1.61	0.216
Subject(Map.)	26	534693.3	20565.1	33.64	0.000
Comp.*Subject(Map.)	26	18809.4	723.4	1.18	0.336
Resp.*Subject(Map.)	26	31689.2	1218.8	1.99	0.042
Error	26	15895.9	611.4		
Total	111	672217.2			

iii). Means computed using LOG (RT).

Source	DF	SS	MS	F	P value
Compatibility	1	0.001014	0.001014	0.24	0.631
Response	1	0.009321	0.009321	1.07	0.311
Mapping	1	0.398711	0.398711	3.16	0.087
Comp.*Resp.	1	0.000004	0.000004	0.00	0.972
Comp.*Map.	1	0.000082	0.000082	0.02	0.891
Resp.*Map.	1	0.002072	0.002072	0.24	0.630
Comp.*Resp.*Map.	1	0.007337	0.007337	2.16	0.154
Subject(Map.)	26	3.279613	0.126139	37.08	0.000
Comp.*Subject(Map.)	26	0.111645	0.004294	1.26	0.278
Resp.*Subject(Map.)	26	0.227224	0.008739	2.57	0.010
Error	26	0.088448	0.003402		
Total	111	4.125472			

10.2.3. ANOVA table for the materials analysis.

Means computed after removing reaction times more than 2 standard deviations from overall subject means.

Source	DF	SS	MS	F	P value
Compatibility	1	617.6	617.6	0.70	0.410
Response	1	472.6	472.6	0.78	0.383
Mapping	1	138805.1	138805.1	371.26	0.000
Comp.*Resp.	1	1239.9	1239.9	2.04	0.161
Comp.*Map.	1	0.5	0.5	0.00	0.972
Resp.*Map.	1	474.0	474.0	1.14	0.293
Comp.*Resp.*Map.	1	2536.2	2536.2	6.08	0.018
Object(Comp.)	38	33766.2	888.6	2.13	0.011
Resp.*Object(Comp.)	38	23082.4	607.4	1.46	0.126
Map.*Object(Comp.)	38	14207.1	373.9	0.90	0.632
Error	38	15857.8	417.3		
Total	159	231059.4			

10.2.4. ANOVA table for the error rate analysis.

Source	DF	SS	MS	F	P value
Compatibility	1	0.223	0.223	0.03	0.874
Response	1	32.143	32.143	1.00	0.327
Mapping	1	43.750	43.750	1.24	0.276
Comp.*Resp.	1	5.580	5.580	0.62	0.439
Comp.*Map.	1	37.723	37.723	4.31	0.048
Resp.*Map.	1	89.286	89.286	2.77	0.108
Comp.*Resp.*Map.	1	37.723	37.723	4.18	0.051
Subject(Map.)	26	918.304	35.319	3.91	0.000
Comp.*Subject(Map.)	26	227.679	8.757	0.97	0.531
Resp.*Subject(Map.)	26	837.946	32.229	3.57	0.001
Error	26	234.821	9.032		
Total	111	2465.178			

10.2.5. Simple interaction effects. Means computed after removing reaction times more than 2 standard deviations from overall subject means.

i). ANOVA table for the H_C mapping.

Source	DF	SS	MS	F	P value
Subject	13	216836.4	16679.7	88.41	0.000
Compatibility	1	375.9	375.9	1.66	0.220
Response	1	525.3	525.3	0.58	0.458
Subject*Comp.	13	2947.2	226.7	1.20	0.373
Subject*Resp.	13	11675.9	898.1	4.76	0.004
Comp.*Resp.	1	143.7	143.7	0.76	0.399
Error	13	2452.5	188.7		
Total	55	234956.9			

ii). ANOVA table for the L_C mapping.

Source	DF	SS	MS	F	P value
Subject	13	368544.3	28349.6	60.67	0.000
Compatibility	1	57.0	57.0	0.08	0.786
Response	1	0.0	0.0	0.00	0.996
Subject*Comp.	13	9594.7	738.1	1.58	0.210
Subject*Resp.	13	11081.7	852.4	1.82	0.146
Comp.*Resp.	1	1658.2	1658.2	3.55	0.082
Error	13	6074.2	467.2		
Total	55	397010.1			

10.3. Statistical analyses and summary tables for Experiment 6b.

10.3.1. Table of means, standard deviations and *% errors* for Experiment 6b by conditions. Response times more than 2 sds from overall subject means excluded.

	Mapping			
	H_C		L_C	
	Response		Response	
Compatibility	C/wise	AC/wise	C/wise	AC/wise
C/wise	345.8	365.79	355.45	363.5
	89.50	108.89	80.80	74.07
	4.64	*5.89*	*7.14*	*7.14*
AC/wise	360.13	371.27	367.12	357.10
	90.05	109.88	74.70	72.40
	6.61	*7.32*	*8.04*	*5.54*

10.3.2. Analysis of variance tables for the analyses by subjects.

i). Means computed after removing reaction times more than 2 standard deviations from subject overall means.

Source	DF	SS	MS	F	P value
Compatibility	1	1100.9	1100.9	5.61	0.026
Response	1	1488.0	1488.0	1.45	0.240
Mapping	1	0.1	0.1	0.00	0.999
Comp.*Resp.	1	1267.7	1267.7	9.37	0.005
Comp.*Map.	1	369.0	369.0	1.88	0.182
Resp.*Map.	1	1917.6	1917.6	1.86	0.184
Comp.*Resp.*Map.	1	148.5	148.5	1.10	0.304
Subject(Map.)	26	782151.9	30082.8	222.26	0.000
Comp.*Subject(Map.)	26	5102.4	196.2	1.45	0.175
Resp.*Subject(Map.)	26	26742.4	1028.6	7.60	0.000
Error	26	3519.1	135.4		
Total	111	823807.4			

ii). Means computed on median RT.

Source	DF	SS	MS	F	P value
Compatibility	1	2814.0	2814.0	7.70	0.010
Response	1	2741.3	2741.3	1.61	0.216
Mapping	1	137.3	137.3	0.01	0.944
Comp.*Resp.	1	2775.1	2775.1	11.95	0.002
Comp.*Map.	1	418.9	418.9	1.15	0.294
Resp.*Map.	1	4225.1	4225.1	2.48	0.128
Comp.*Resp.*Map.	1	1995.0	1995.0	8.59	0.007
Subject(Map.)	26	712790.0	27415.0	118.06	0.000
Comp.*Subject(Map.)	26	9503.4	365.5	1.57	0.127
Resp.*Subject(Map.)	26	44357.1	1706.0	7.35	0.000
Error	26	6037.5	232.2		
Total	111	787794.7			

iii). Means computed on LOG (RT).

Source	DF	SS	MS	F	P value
Compatibility	1	0.001557	0.001557	0.85	0.364
Response	1	0.006170	0.006170	0.83	0.371
Mapping	1	0.002942	0.002942	0.01	0.905
Comp.*Resp.	1	0.007451	0.007451	4.91	0.036
Comp.*Map.	1	0.001419	0.001419	0.78	0.386
Resp.*Map.	1	0.011876	0.011876	1.60	0.218
Comp.*Resp.*Map.	1	0.002408	0.002408	1.59	0.219
Subject(Map.)	26	5.286369	0.203322	134.09	0.000
Comp.*Subject(Map.)	26	0.047394	0.001823	1.20	0.321
Resp.*Subject(Map.)	26	0.193510	0.007443	4.91	0.000
Error	26	0.039425	0.001516		
Total	111	5.600521			

10.3.3. ANOVA table for the materials analysis.

Means computed after removing response times greater than 2 standard deviations from subject overall means.

Source	DF	SS	MS	F	P value
Compatibility	1	1161.7	1161.7	1.97	0.169
Response	1	1903.9	1903.9	4.58	0.039
Mapping	1	17.8	17.8	0.05	0.819
Comp.*Resp.	1	1521.5	1521.5	3.66	0.063
Comp.*Map.	1	891.3	891.3	2.66	0.111
Resp.*Map.	1	3436.1	3436.1	8.45	0.006
Comp.*Resp.*Map.	1	346.7	346.7	0.85	0.362
Object(Comp.)	38	22462.0	591.1	1.45	0.127
Resp.*Object(Comp.)	38	15808.7	416.0	1.02	0.472
Map.*Object(Comp.)	38	12720.9	334.8	0.82	0.724
Error	38	15448.9	406.5		
Total	159	75719.3			

10.3.4. ANOVA table for the analysis of subject error rates.

Source	DF	SS	MS	F	P value
Compatibility	1	12.56	12.56	1.86	0.184
Response	1	0.50	0.50	0.03	0.866
Mapping	1	20.15	20.15	0.55	0.466
Comp.*Resp.	1	16.13	16.13	0.99	0.330
Comp.*Map.	1	29.52	29.52	4.38	0.046
Resp.*Map.	1	34.88	34.88	2.01	0.168
Comp.*Resp.*Map.	1	6.75	6.75	0.41	0.526
Subject(Map.)	26	956.36	36.78	2.25	0.022
Comp.*Subject(Map.)	26	175.11	6.74	0.41	0.986
Resp.*Subject(Map.)	26	450.56	17.33	1.06	0.443
Error	26	425.56	16.37		
Total	111	2128.07			

10.4. Combined ANOVA table on the data from Experiments 6a and 6b. Response times more than 2 sds from overall subject means excluded.

Source	DF	SS	MS	F	P value
Compatibility	1	1364	1364	4.02	0.050
Response	1	1494	1494	1.57	0.216
Mapping	1	49495	49495	1.88	0.176
Experiment	1	198733	198733	7.56	0.008
Comp.*Resp.	1	1564	1564	6.75	0.012
Comp.*Map.	1	380	380	1.12	0.295
Comp.*Exp.	1	100	100	0.29	0.590
Resp.*Map.	1	1807	1807	1.90	0.174
Resp.*Exp.	1	253	253	0.27	0.609
Map.*Exp.	1	49340	49340	1.88	0.177
Comp.*Resp.*Map.	1	1223	1223	5.28	0.026
Comp.*Resp.*Exp.	1	117	117	0.50	0.481
Comp.*Map.*Exp.	1	59	59	0.17	0.679
Resp.*Map.*Exp.	1	377	377	0.40	0.532
Comp.*Resp.*Map.*Exp.	1	315	315	1.36	0.249
Subject(Map. Exp.)	52	1367533	26299	113.53	0.000
Comp.*Subj.(Map. Exp.)	52	17644	339	1.46	0.086
Resp.*Subj.(Map. Exp.)	52	49500	952	4.11	0.000
Error	52	12046	232		
Total	223	1753343			

10.5. Statistical analyses and summary tables for Experiment 7.

10.5.1. Analysis of variance tables for the analyses by subjects.

i). ANOVA table for the analysis on response times after excluding those more than 2 standard deviations from overall subject means.

Source	DF	SS	MS	F	P value
Compatibility	1	1139	1139	2.31	0.137
Response	1	13527	13527	12.94	0.001
Mapping	1	116661	116661	4.57	0.039
Comp.*Resp.	1	3469	3469	7.13	0.011
Comp.*Map.	1	20	20	0.04	0.843
Resp.*Map.	1	8816	8816	8.43	0.006
Comp.*Resp.*Map.	1	8383	8383	17.23	0.000
Subject(Map.)	36	919885	25552	52.51	0.000
Comp.*Subject(Map.)	36	17718	492	1.01	0.487
Resp.*Subject(Map.)	36	37640	1046	2.15	0.012
Error	36	17518	487		
Total	151	1144776			

ii). ANOVA table for the analysis on Median RT.

Source	DF	SS	MS	F	P value
Compatibility	1	121.8	121.8	0.25	0.621
Response	1	15512.6	15512.6	12.16	0.001
Mapping	1	88121.7	88121.7	4.02	0.052
Comp.*Resp.	1	2679.2	2679.2	4.41	0.043
Comp.*Map.	1	160.2	160.2	0.33	0.571
Resp.*Map.	1	2108.0	2108.0	1.65	0.207
Comp.*Resp.*Map.	1	5789.1	5789.1	9.52	0.004
Subject(Map.)	36	788632.0	21906.4	36.02	0.000
Comp.*Subject(Map.)	36	17666.8	490.7	0.81	0.738
Resp.*Subject(Map.)	36	45918.4	1275.5	2.10	0.015
Error	36	21894.3	608.2		
Total	151	988604.0			

iii). ANOVA table for the analysis on LOG (RT).

Source	DF	SS	MS	F	P value
Compatibility	1	0.003054	0.003054	1.08	0.305
Response	1	0.087339	0.087339	14.61	0.001
Mapping	1	0.563115	0.563115	4.36	0.044
Comp.*Resp.	1	0.019798	0.019798	6.50	0.015
Comp.*Map.	1	0.000098	0.000098	0.03	0.853
Resp.*Map.	1	0.061690	0.061690	10.32	0.003
Comp.*Resp.*Map.	1	0.054717	0.054717	17.97	0.000
Subject(Map.)	36	4.650756	0.129188	42.42	0.000
Comp.*Subject(Map.)	36	0.101562	0.002821	0.93	0.590
Resp.*Subject(Map.)	36	0.215223	0.005978	1.96	0.023
Error	36	0.109635	0.003045		
Total	151	5.866988			

10.5.2. ANOVA table for the materials analysis.

Response times more than 2 standard deviations from subjects overall means discarded.

Source	DF	SS	MS	F	P value
Compatibility	1	1338.2	1338.2	2.41	0.129
Response	1	13295.4	13295.4	33.49	0.000
Mapping	1	128016.8	128016.8	336.10	0.000
Comp.*Resp.	1	4330.2	4330.2	10.91	0.002
Comp.*Map.	1	15.9	15.9	0.04	0.839
Resp.*Map.	1	8931.5	8931.5	18.64	0.000
Comp.*Resp.*Map.	1	8925.7	8925.7	18.63	0.000
Object(Comp.)	38	21078.9	554.7	1.16	0.327
Resp.*Object(Comp.)	38	15085.3	397.0	0.83	0.718
Map.*Object(Comp.)	38	14473.6	380.9	0.79	0.759
Error	38	18208.3	479.2		
Total	159	233699.8			

10.5.3. ANOVA table for the error rate analysis.

Source	DF	SS	MS	F	P value
Compatibility	1	0.658	0.658	0.07	0.799
Response	1	42.105	42.105	2.24	0.143
Mapping	1	4.112	4.112	0.18	0.678
Comp.*Resp.	1	0.658	0.658	0.09	0.765
Comp.*Map.	1	8.059	8.059	0.81	0.375
Resp.*Map.	1	13.322	13.322	0.71	0.405
Comp.*Resp.*Map.	1	1.480	1.480	0.20	0.654
Subject(Map.)	36	843.257	23.424	3.24	0.000
Comp.*Subject(Map.)	36	360.033	10.001	1.38	0.168
Resp.*Subject(Map.)	36	675.822	18.773	2.60	0.003
Error	36	260.362	7.232		
Total	151	2209.868			

10.5.4. ANOVA tables for the simple interaction effects.

i). ANOVA table for the High pitch tone - Precision grip response mapping (H_PRE). Means computed after removing reaction times more than 2 standard deviations from overall subject means.

Source	DF	SS	MS	F	P value
Subject	18	255750.9	14208.4	24.50	0.000
Compatibility	1	728.6	728.6	1.19	0.289
Response	1	22092.0	22092.0	26.33	0.000
Subject*Comp.	18	10994.5	610.8	1.05	0.457
Subject*Resp.	18	15101.0	838.9	1.45	0.221
Comp.*Resp.	1	11319.2	11319.2	19.52	0.000
Error	18	10438.7	579.9		
Total	75	326424.9			

ii). ANOVA table for the High pitch tone - Power grip response mapping (H_POW). Means computed after removing reaction times more than 2 standard deviations from overall subject means.

Source	DF	SS	MS	F	P value
Subject	18	664134	36896	93.82	0.000
Compatibility	1	430	430	1.15	0.297
Response	1	251	251	0.20	0.660
Subject*Comp.	18	6723	374	0.95	0.543
Subject*Resp.	18	22539	1252	3.18	0.009
Comp.*Resp.	1	533	533	1.36	0.259
Error	18	7079	393		
Total	75	701690			

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