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Callosal connectivity and interhemispheric bilateral advantage: a Diffusion Tensor Imaging study

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Abstract

There is wide acknowledgement that the cerebral hemispheres do not operate in isolation when processing complex visual stimuli (Singh, 2000; Schulte & Muller-Oehring, 2010). Patterns of interhemispheric communication are believed to be integral to such cognitive abilities, yet the circumstances under which communication takes place and the nature of information being processed is poorly understood. This experiment addresses the role of interhemispheric communication regarding inter-individual differences in underlying white matter (WM) relating to the matching facial identity. Several studies have already documented the role of WM in processing abilities such as with differences in gender, age and disease (Schulte & Muller-Oehring, 2010). This study though, specifically aimed at establishing whether a bilateral advantage (BA) in processing facial identity of 21 healthy individuals, could too be explained by inter-individual differences in underlying callosal microstructure. In a behavioural task, participants performed a perceptually complex physical identity task using facial stimuli presented to either one hemisphere or split between both before making a key press in response to identity. Fractional anisotropy (FA) and Tract-based Spatial Statistics (TBSS) analysis of diffusion tensor imaging (DTI) was employed to measure the underlying tissue structure of the brain in areas of the corpus callosum (CC). This was then correlated with the BA data collected from the behavioural task. Results revealed no significant relationship between BA and individual WM, however tracts identified were in line with prior research and some were seen to be approaching significance.

Introduction

The corpus callosum (CC) is a principal white matter (WM) bundle linking the neocortical areas of the cerebral hemispheres and is regarded as being essential to hemispheric communication (Schulte & Muller-Oehring, 2010; Gazzinga, 2000). Via the combination of both neuroimaging techniques and behavioural procedures, studies have begun to document empirical evidence for a link between WM microstructure and efficient integration of information between the two hemispheres (Schulte & Muller-Oehring, 2010). More recently, an emerging pattern of results have shown subtle changes in callosal WM as responsible for the differences seen in individuals concerning numerous cognitive, perceptual and tactile tasks (Fling, Peltier, Bo, Welsh & Seilder, 2011). Yet, very few document inter-individual differences in the morphology of healthy individuals regarding tasks of interhemispheric integration, especially in the case of facial processing. This investigation aims to further clarify the neural foundations of callosal communication regarding a popular interhemispheric effect of bilateral advantage (BA), specifically focusing on how differences in WM tracts of the CC may relate to a person's ability to process facial identity. It is hoped a greater insight into the process of callosal communication can be obtained, which may also allow for a more complete understanding of interhemispheric interaction (IHI) in cognitive processing, as well as extending the benefits of this to encompass more perceptually complex stimuli.

The human brain consists of two hemispheres connected by a set of commissural fibres crossing at the midline (Zaidel & Iacoboni, 2003). These interhemispheric connections ensure information received at one hemisphere is then accessible to the other (Zaidel & Iacoboni, 2003). The human brain has three major commissures: the CC, anterior, posterior (hippocampal) (Zaidel & Iacoboni, 2003). The CC specifically is the largest; having many intra and interhemispheric myelinated axonal projections interconnecting a large sum of cortical regions (Raybaud, 2010); and is considered to be the most important commissure interconnecting both cerebral hemispheres (Zaidel & Iacoboni, 2003). Early experiments by Sperry illustrated the specialised nature of the human visual system; anything presented to the right visual field (RVF) is projected exclusively to the left hemisphere (LH), where information in the left visual field (LVF) is sent to the right hemisphere (RH) (Kalat, 1998). Surgical interventions (Callostomies) aimed at the prevention of epileptic seizures (Van der Knaap & Van der Ham, 2011) have led to the unique understanding into this structures role in interhemispheric transfer (IHT) of lateralised information (Gazzaniga, 2005). Studies of those who have undergone complete or partial sectioning of the CC show information, for example, is blocked to the opposing hemisphere, causing trouble when carrying out bimanual comparisons of tactile stimulus or when comparing stimuli briefly presented to different hemifields (Zaidel & Iacoboni, 2003). Further, some lateralised functions like language attributed to the LH, are shown to depend in part on the integration of both hemispheres (Sternberg &Sternberg 2011). Hence reinforcing the idea that at least for some cognitive processes an amount of interhemispheric collaboration is needed to fuse perceptual information together.

Numerous aspects of interhemispheric communication have been studied over the years, each using a variety of experimental approaches. The divided visual field, originally adopted and used by Diamond and Beaumont (1971), is one popular method (Mohr, Langrebe & Schwienberger, 2002). Stimuli are briefly presented

tachistoscopically to the RVF, LVF or simultaneously to both visual fields (BVF), referred to as a bilateral condition (Mohr et al, 2002). Importantly within the latter condition, necessary information to complete a task is divided between the hemispheres, and so cooperation between the two must be conducted (Mohr et al, 2002). By comparing results obtained across the conditions (unilateral condition vs. bilateral condition), a measure of IHI can be gained (Mohr et al, 2002) and is used as a foundation of exploration into interhemispheric communication.

A line of enquiry regards the processing capacity of the brain. It is proposed that the pooling of processing resources from both hemispheres is advantageous when tasks are highly demanding (Compton, 2002; Banich & Belger, 1990). Performance is improved when a task requires the hemispheres to work together rather than in isolation (Compton, 2002), even if response time (RT) is delayed (Westerhausen et al, 2006). Typically, investigations utilise a paradigm whereby a triangular array of three stimuli are flashed tachiscopically in front of participants and a choice of similarity is made between the bottom and the top items (Banich & Belger, 1990). On some of these trials, the matching items are shown in opposite visual fields, and thus interhemispheric communication is needed to reach a match decision. But on others, the matching item appears in the same visual field, such that interhemispheric communication is not needed (Compton, 2002). Numerous studies (Banich & Belger, 1990; Belger & Banich, 1992) have shown performance to be fairly consistent for within and across-field matches when the task is considered simple like matching two physically identical letters (A and A). Yet when complexity is increased, as in matching two letters by name (A and a), whereby a further computational step of case sensitivity is needed, performance was quicker and subsequently more accurate for across-field trials. BA has been widely reported in several tasks of adding, comparison of number values, identification of upright and inverted letters (Merola & Liedermann, 1990), and the matching of Chinese characters (Zhang & Feng, 1999). All show similar patterns of results, with the less complex tasks of comparing digits, Chinese characters and letters, producing no BA (Beumont & Diamond, 1975; Belger & Banich 1992; Zhang & Feng, 1999). In such cases when a decision needed is less complex, interhemispheric interaction can be considered providing little benefit to processing (Welcome & Chiarello, 2008).

Despite this, tasks use stimuli which may underestimate the complexity of tasks faced in everyday life, thus underestimating the real advantage gained by hemispheric cooperation (Compton, 2002). To date, few studies have directed interest towards interhemispheric processing of the human face, with only two (Geffen, Bradshaw & Wallace, 1971; Compton, 2002) having extended research on the influence of task complexity using facial stimuli. Compton (2002), for example, conducted a face matching task whereby participants matched unfamiliar faces on their expressed emotion (experiment 1) or identity (experiment 2). Results revealed that for both match-type, performance was greater for across field matches compared to within. Moreover, a greater advantage was seen in the across hemisphere condition when the difficult task of character identity was set. This further supports the idea that hemispheric cooperation is beneficial when completing perceptually complex tasks.

A further line of research finding has found that the time taken to transfer information across the hemispheres varies in individuals. A relationship between

interhemispheric transfer time (IHTT) and handedness for instance has been found. Bernard and Seilder (2008) found more strongly handed people have slower IHTT's; with left handlers having more efficient interaction across the hemispheres, than their right handed counterparts on measurements of a letter matching task (Cherbuin & Brinkman, 2006a, 2006b). This was further supported by Bernard and Seidler (2008) whom found significant differences between crossed-uncrossed differences (CUD) as measure of IHI in left and right handlers; with left-handed participants having significantly faster CUDs.

Neuroimaging techniques like Magnetic Resonance Imaging (MRI) and Functional Magnetic Resonance Imaging (Fmri) have revealed such differences in individuals as dependent on morphological changes of specific WM fibre tracts linked with the transmission of information needed for tasks and so of the CC. (Turken et al, 2008; Singh 2000). Callosal size, for example, affects transmission speed, with increases in callosal size allowing for better hemispheric communication (Caminiti et al, 2009) and age associated degrading of WM being related with lower performances in motor and cognitive tasks (Sullivan, Rohlfing &Pfefferbaum, 2010). Moreover, Sullivan and Pfefferbaum (2006) reviewed studies which examined the structure of WM including the CC and found an age-related decline in fractional anisotropy (FA) which is thought to reflect reduced structural integrity, with areas of CC (the Genu and middle third) being linked as responsible (Ota et al, 2006). The Genu specifically contains several small diameters of unmyelinated and thinly myelinated axons which are highly susceptible to degeneration and demyelination with age (Bennett, Madden, Vaidya, Howard & James, 2010). Other areas of the CC are splenial fibres which affect the neural interaction between the left and right hemispheres (Mori, Wakana, Van Ziji & Nagae, 2005). Such findings give support to Field's (2008) argument that differences in callosal structure directly impact brain activity and latter behaviour, while also permitting the question whether differences in BA may also be explained by underlying structural differences.

To investigate this, Diffusion Tensor Imaging (DTI) was used within this experiment. Also known as diffusion magnetic resonance imaging (dMRI) (Le Bihan, 2003), it is an increasingly popular research method, allowing insight into brain connectivity, due to advances in this technology permitting non-invasive measurements of brain tissue microstructure (Soares, Marques, Alves & Sousa 2013; Le Bihan et al 2001). This is achieved via measuring the three-dimensional diffusion of water molecules (Alexander, Lee, Lazar & Field, 2007) and transportation of ions (Geeter, Crevecoeur, Dupré, Hecke & Leemans, 2012) as a function of spatial processing (Alexander et al, 2007). Water molecules diffuse differently along tissues, with type, presence of barriers, integrity and architecture (diameter and degree of myelination) all having influence. Unrestricted water molecules move randomly (isotopically); but in the presence of obstacles which reduce free motion as in WM tracts, movement is directionally dependent (anisotropic) (Alexander et al, 2007). The interaction of molecules within cell barriers then allows for information to be gained about its orientation and anisotropy (Chenevert, Brunberg & Pipe, 1990; Beauleiu, 2002). Diffusivity is larger in directions along fibres rather than perpendicular to them (Chenevert et al, 1990) and its overall direction can be described mathematically via a tensor, characterised by three eigenvectors and corresponding eigenvalues (Wang & Melham, 2005). The eigenvector linked to the biggest eigenvalue indicates the predominant orientation of fibres in a set voxel (Wang & Melham, 2005). A common

measure derived is FA, which reflects the degree of diffusion in constrained space due to local tissue properties (Turken et al, 2008). This measure has been utilised to reveal links between psychological variables and subtle changes in properties of WM, argued to be inaccessible via other imaging modalities (Schelute, Sullivan, Muller-Oehring, Adalsteinsson & Pfefferbaum, 2005). Tractography then determines the diffusion properties in a single voxel and so the evaluation of diffusion within other voxels and WM fibre pathways (Zhu et al, 2014). A highly plausible estimation of the brain's WM trajectories can then be generated, which when utilised in allows for the measurement of brain regions involved in specific neural processes (Alexander et al., 2007), like for the analysis of individual microstructures underlying BA of facial processing.

The present study examined the effects of underlying WM of the CC regarding BA in a group of healthy individuals, through extending research previously conducted by Compton (2002). In particular, it explicitly tested this by creating an increase in bilateral versus unilateral processing via the use of the Marie-Banich Paradigm of IHI (Banich & Belger, 1990), whereby innocuous stimuli (faces), similar to those in Compton (2002), were presented to either the same or opposite hemispheres. To allow for a BA the proven task of Compton's second experiment was used: identity matching. It is hoped that BA scores will differ between participants and these differences will correspond to underlying anatomical differences in WM when regressed against DTI data. Specifically, this will be conducted via the Tract Based Spatial Statistics (TBSS) software.

Method

Participants

Twenty-one (N=21, 14 women, seven men, M_{age} = 21.5, age range: 18-51, SD=7.4) students of the University of Plymouth voluntarily participated in this study and received either a participation point or £4 for participation. Two of the participants were experimenters of the current study and prior to the experiment, all participants had completed a three year experimental investigation by the supervisor Matt Rosser on the neuropsychology of reasoning (Economic and Social Research Council Grant RES- 062-23-3285. Dual processes in reasoning: A neuropsychological study of the role of working memory). All participants of this were neurologically-normal at the time of DTI data acquisition, with normal or above normal cognitive capacity as assessed by the Welchsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). The prior study had already obtained (Faculty of Science) ethical clearance and the use of the data collected had received permission for use in future research. Diffusion-tensor image (DTI) data collected from participants in the earlier study were used in the present investigation. No other biographical data was collected.

To guarantee that all participants matched those with prior DTI files, they were contacted electronically via an email written by the supervisor. This was then followed up, on agreement from the participant, by a further email from the experimental researchers of the project and given a code which would allow them to book an appropriate time slot on the school's Psychology Participation Pool system.

Materials

Diffusion tensor imaging

All participants underwent MRI on a 1.5-Telsa Phillips Intera scanner. DTI data itself was created through the use of a diffusion weighted single-shot spin-echo EPI sequence, which was performed along 32 independent directions, with a b-value of 1000 s/mm^2. A reference image (b=0 s/mm^2) was also acquired.

Behavioural data

At the start of the experiment, a printed information sheet and consent form were provided to each participant. Each participant was made aware that any data collected from the process would be kept confidential and only accessible by the experimental researchers and supervisor. The computers used within the experiment were Phillips Brilliance 221P3LPY LED widescreen 200 inch monitors set at 1280x1034 resolution. One participant however was tested using a Toshiba Tecra R840-10Z laptop set at 2048x1536 resolution. The experiment itself was run using E-Prime software version 2.0 (Psychology Software Tools). Participants were positioned in front of the monitor at a set viewing distance of 57 centimetres (cm) using a table mounted chinrest.

On successful completion of this process, participants then received a written document (debrief) summarising details of the studies design such as what we planned to achieve and the supervisor's contact details in case of any queries post completion.

Visual stimuli

Nine digitised colour photographs from the NimStim.set were used. The nine photographs consisted of two female faces and one male face, each displaying a neutral, angry and happy expression.

The stimulus array for each trial consisted of three faces placed in a triangular formation against a plain white backdrop. Figure 1 and 2 illustrate a sample stimulus array. Two of the faces were presented above the point of fixation and one below. Each of the faces displayed were 7 cm by 6 cm. The top two were centred at 2.5 ° above fixation and 2° to the left and right of fixation. The bottom face was positioned 2° below fixation and 2.5° to the left and right of fixation. The task required participants to indicate whether the identity of the face displayed at the bottom matched that of either faces presented at the top. Instructions emphasised that the matching of faces may also show the same face displaying a different or the same emotional expression.

A total of 64 trials were created from a crossed combination of five separate factors; hand used (left/right), emotion matching (matched/no-match), bilaterally (acrossVF/withinVF), target field (LVF/RVF) and identity match (match/no-match). Half were matched on expressed emotion, with one of the top faces matching the bottom, and the other half where the bottom face matched neither of the top two. Of this, half were matched on both expression and character identity (i.e. the matching faces were physical identical and displayed the same expression of angry, happy or neutral) and half were matched on expression but not character identity. In addition, the target face could be shown in either the LVF or the RVF and finally participant

responses could be made with either their left or right hand

Figure 1*:* Example of the across hemisphere match trial. Here the bottom face displayed is matched on character identity with that of the top right face displayed within the opposite visual field. Additionally both these faces are displaying the same facial (angry) expression.

Figure 2: Example of a within hemisphere match trial. Here the bottom face displayed within the same visual field is matched on character identity with that of the top right face. Additionally both these faces are displaying the same facial (angry) expression.

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Design and procedure

Participants completed the experiment individually in groups no larger than three people. The precise time of the testing varied between 9:00am to 4:00pm as the experiment was conducted during timetabled university laboratory hours. Each participant entered a room containing between five to twelve open-ended cubicles and a computer with the experiment already open ready for participants to begin. All participants were given a brief and consent form before being reminded that they were free to withdraw from the study at any time. None did so. Instructions were then issued verbally and displayed on the computer screen. The following is a brief version of the instructions received:

‘“Each trial will start with a fixed fixation point (cross) in the middle of the screen which will remain in place for the entirety of the experiment. After a very short period of time facial stimuli will then be flashed either side of fixation and you will be

required to make a judgement by hitting the response key, as to whether you think the bottom face matches either of the top two faces on character identity. Additionally the faces seen may also match on emotional expression. The presentation of stimuli is very quick, so please try to respond as quickly as possible"

At this point the experiment was started and as a control measure, each participant was asked to place their chin on a table-mounted chin rest, at a fixed viewing distance of 57 cm from the computer monitor.

The study itself consisted of 64 trials, divided into four experimental blocks. The blocks were separated by short rest periods requiring the participant to press the response key (h key) in order to start the next block. The order of each trial within each block was randomised by the computer software. No practice trials were given before starting the experiment. Each trial contained a set fixation point which remained in sight across the entirety of the experimental trial, before three facial stimuli were then flashed for a total period of 1.5 seconds (s). Participants were instructed to make a speeded response to seeing the flashed stimuli presented and to maintain fixation with the cross at all times during the experiment. The facial stimuli were positioned so that the target face remained below either the right or left of fixation and the two probe faces were above fixation, one on the left and the other on the right (as shown in Figures 1 and 2). On presentation of the stimuli each participant was required to make a decision relating to character identity. If they believed the bottom (target) face matched either of the top faces, they were to indicate by pressing the "h" key on the keyboard. Responses were made with either the left or right index finger, with written instructions given on the screen prior to each experimental block as to which hand to use.

Imaging data acquisition, pre-processing and analyses

Pre-processing of DTI images

In order to process the scanned data collected via diffusion weighted imaging (DWI), data was pre-processed via FSL FDT (Behrens 2003a; Behrens 2003b; Jbabdi, Sotiropoulos, Savio, Grana & Behrens, 2012). All participants scanned data (N=21) were converted via software tool dcm2nii to a Neuroimaging Informatics Technology Initiative (NIfTI) format. To exclude any eddy-current induced distortions or motion artefacts, all images were eddy-current corrected, ensuring all data was clean. Finally, DTIFIT was completed allowing built diffusion tensor models and fractional anisotropy (FA) maps to be attained.

An example of the output produced through this analytical process can be seen in Figure 3.

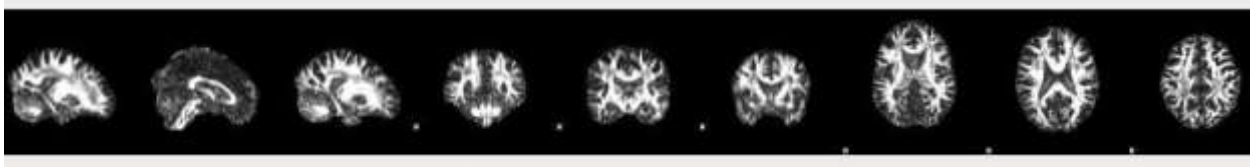

Figure 3*:* FA slices for participant 1 following DTIFIT process (n=1)

Tract-Based Spatial Statistics (TBSS) analysis

After data was pre-processed via FSL FDT, TBSS approach as part of FSL version 3.1.8 (Smith et al, 2004) was used to perform whole brain statistical analysis within white matter centres. Spatial normalisation was achieved through warping all FA images to a 1x1x1m^3 FMRIB58_FA Standard template in MNI152 space using

FMRIB's non-linear regression tool (FNIRT V1.0). To then determine the relationship between auditory modulation (AudMod) of representational momentum (RM) and the brains structural connectivity, individual measures of AudMod effect were regressed against FA data within the white matter skeleton by TBSS. This was created from all participant (n=21) warped FA maps being averaged to create a mean FA template, from which an FA skeleton was created (FA> 2.0). The threshold used being pre-determined by TBSS. The image was set to show green, in order to allow all tracts common in participant brains to be seen. The behavioural index (BA) was then regression against the FA images, whereby all participants (n=21) spatially normalised FA data was overlaid onto the skeleton and fed into voxel-wise statistics, where 10,000 permutations of the data were generated through the use of FSL randomise (Winkler Ridgway, Webster, Smith & Nichols 2014)

An example of the output produced from this process can be seen in Figures 4 and 5, where the output of common white matter pathways in all participants can be seen in Figure 4 and calculations of mean FA for one participant can be seen in Figure 5.

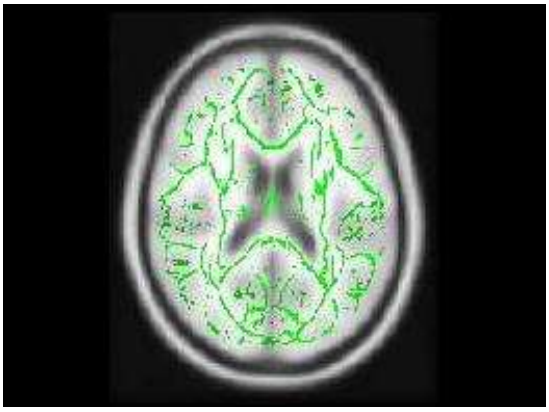

Figure 4: Common white matter pathways produced though the combination all participants, within the mean FA skeleton as shown from a transverse viewpoint. Green specifies the individual pathways and the grey and white areas the surrounding brain area.

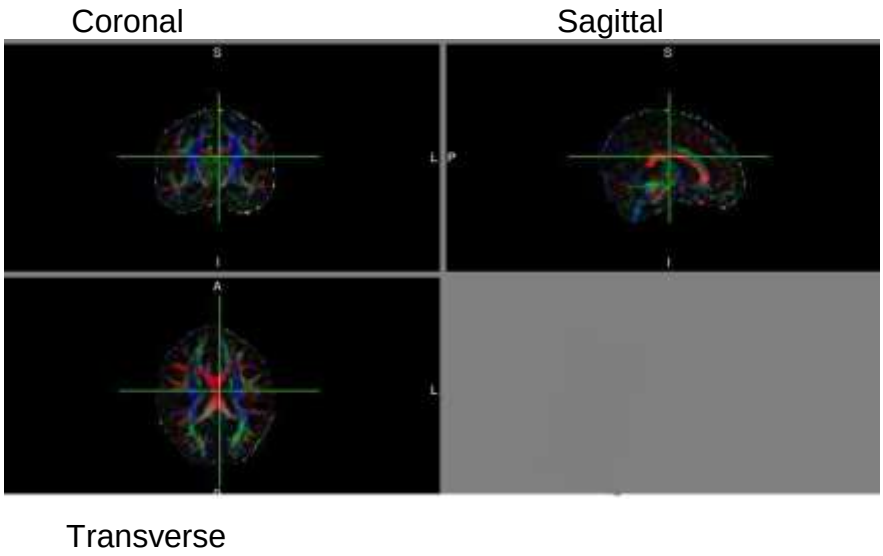

Figure 4: Mean FA analysis. FA scan for participant 1 showing all white matter diffusion pathways in the brain, whereby the principle diffusion directions are indicated by colour. Red specifies a diffusion pathway in a voxel travelling from left to right, blue head to foot, and green from back to front (n=1).

Fibre tract identification

White matter tracts were identified through the use of the Johns Hopkins University (JHU) WM atlas (Mori et al, 2005; Hua et al, 2008), the Johns Hopkins University (JHU) tractography atlas (Mori et al 2005; Hua et al, 2008) and the Harvard-Oxford Cortical Structural (Makris, Goldstien, Kennedy, Hodge, Caviness, Faraone, Tsuang & Seildman, 2007) were consulted to identify brain areas linked with identified white matter tracts. Figure 6 shows a representation of this.

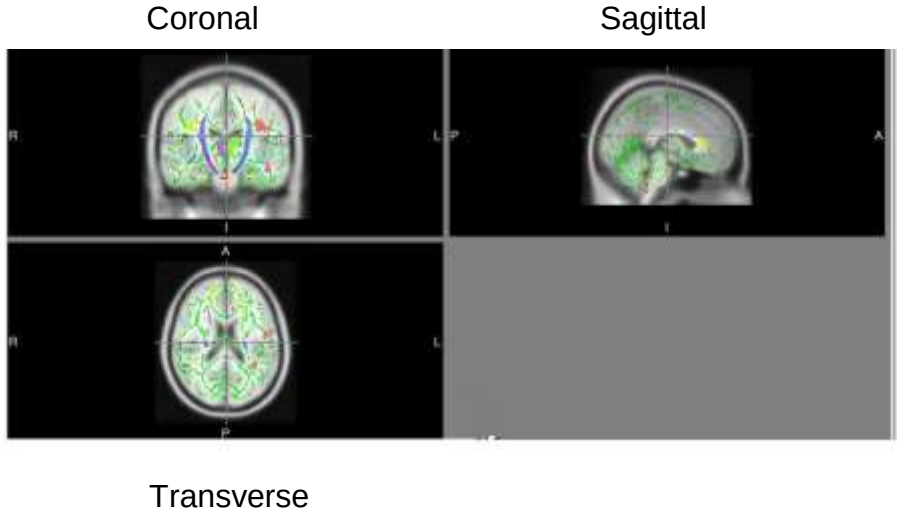

Figure 6: Result of white matter tractography performed on participants and the identification of specific brain areas. White matter tracts are highlighted in green, with specific areas of the brain being shown as various coloured patches (n=21).

Results

Behavioural analysis

Although reaction times (RT's) have been reported in prior research regarding interhemispheric interaction such as in Compton (2002), Banich and Belger, (1990) as well as measuring accuracy, the stimuli used in these studies though were less computationally complex and so can be argued to have reduced sensitivity to accuracy, in addition to not being the primary focus of this experimental study. For this reason, accuracy served as the primary dependent measure within the statistical analysis. Additionally, prior studies (Weisman & Banich, 2000; Banich & Belger, 1998) only use match trial conditions due to mismatch trials being inappropriate in categorising them as either across or within hemisphere.

Each participant's bilateral advantage (BA) score was determined via calculating the difference between accuracy scores of match trials for both within and across visual fields. Within being when the bottom face matched that of another face displayed in the same visual field and across when the bottom face matched the top face given in the opposing visual field. The scores obtained from this were used for analysis.

A Shapiro- Wilk's (S-W) test of normality (p= <0.05), revealed scores of BA across the participant sample were not normally distributed at S-W=.807, df= 21, p.001. The assumption of normality can thus be considered as being violated. A graphical representation of this can be seen in Figure 7.

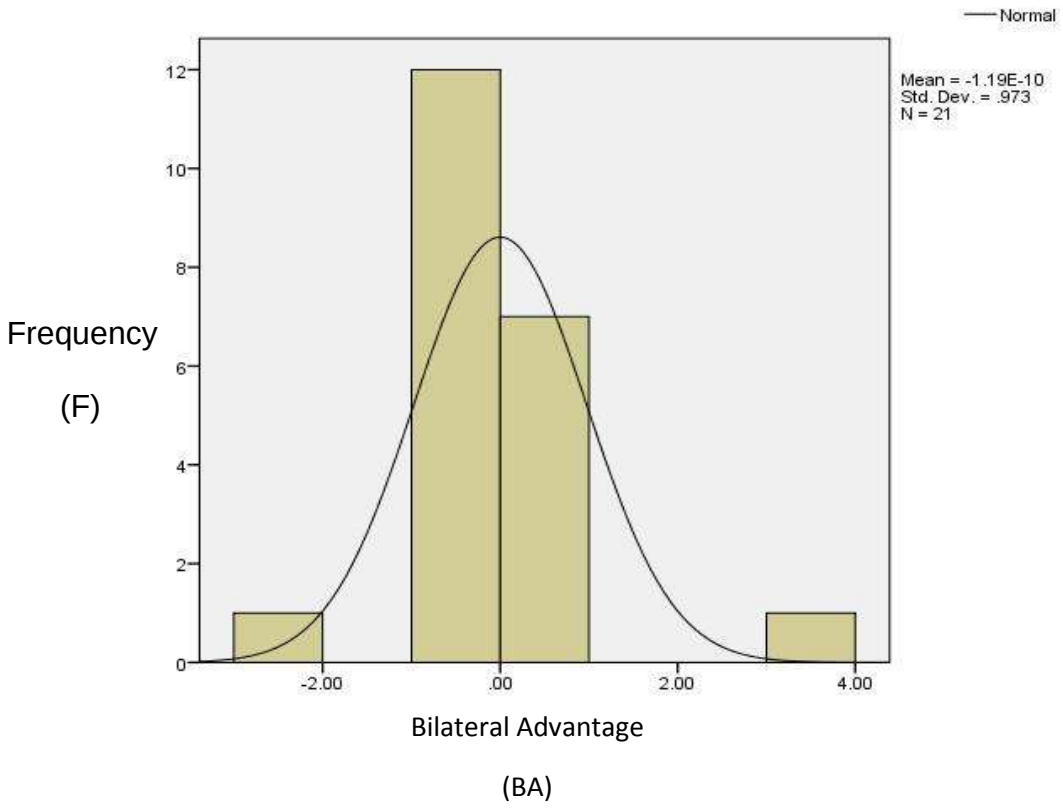

Figure 7: Graph showing the distribution of bilateral advantage (BA) scores obtained by participants (n=21) compared to that of a normal distribution as indicated by the solid black line. From this, you can observe that the BA scores of participants are not normally distributed.

DTI analysis

In investigating the effects of white matter (WM) integrity between participants and the behavioural index of BA, no significant (p<0.05) voxels were revealed. The statistical maps produced did however reveal positive voxels at significance of p=1. These were found in the body of the corpus callosum (Mean FA= 0.57), specifically towards the anterior region (Mean FA= 0.57), the superior longitudinal fasciculus (Mean FA= 0.55) and the associated projection fibres of the right anterior thalamic region (Mean FA= 0.36).

Of the statistical analysis, there was also some suggestion of a significant negative relationship at p= 0.62 in areas relating directly to the corpus callosum and surrounding areas. Although not statistically significant at p<0.05, they could be argued as approaching significance. These near significant voxels were seen to be located within the genu, specifically that of the forceps minor (mean FA= 0.73) and splenium (Mean FA= 0.41) of the corpus callosum, as well as areas of the Fornix (Mean FA=0.41).

A visual representation of these findings can be seen in Figure 8.

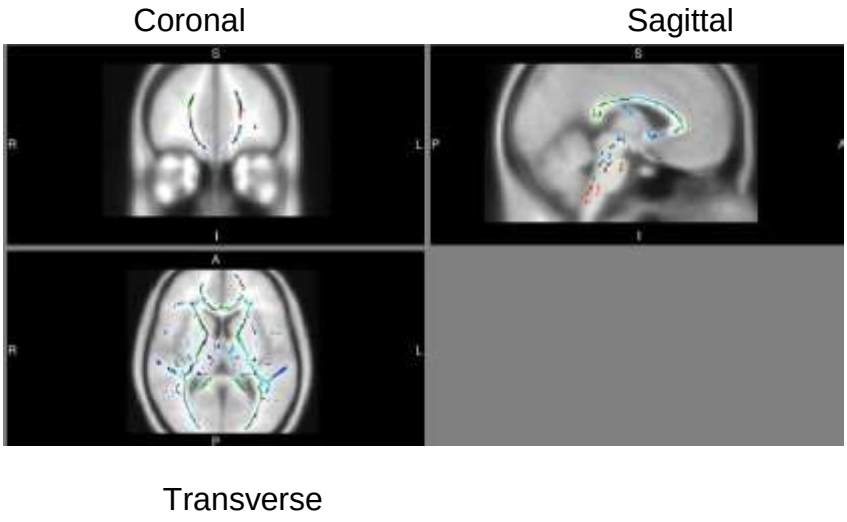

Figure 8: Statistical map showing both the positive and negative non-significant voxels (n=21). Voxels highlighted red indicate voxel of positive non-significance and those in blue indicate voxels of negative non-significance.

Discussion

The main intention of this research was to explore whether a connection could be established between individual white matter microstructure and bilateral advantage (BA) scores. It was predicted that participants white matter tracts (WM) would differ from each other and these would then correspond to differences in BA scores seen from the behavioural task of matching facial identity. Results from Tract-based Statistical Software (TBSS) analysis however indicated no significant (positive or negative) relationships regarding differences in WM tracts and a BA, contrary to this studies prediction. Sample size though may have been a factor relating to this.

Despite this, functional anisotropy (FA) values recorded, although not significant, confirm areas which allow for interhemispheric communication of the two cerebral hemispheres. Areas of the splenium, genu, for instance, were seen to be highlighted, which although not of significance, do mimic areas commented on by prior research (Ota et al, 2006) regarding the transport of information across the two hemispheres via the CC. Mori et al (2005) also comments on the use of both the anterior thalamic regions and splenium as being required for the neural interaction between the left and right hemispheres. Overall, these findings then show further evidence for these tracts being involved in connecting the two hemispheres, but also that the task was able to be performed through the use of both hemispheres, adding to the amount of studies already suggesting for a processing advantage across hemispheres when under highly demanding conditions (Banich & Belger, Compton 2002).

Further to this, tractography did show some WM tracts that are potentially involved with a bilateral advantage effect, with areas of the callosal region (specifically of the genu, splenium and fornix) being seen as approaching significance. Regarding these areas, in particular that of the genu and areas surrounding it, are seen to be highly susceptible to changes in integrity and correlated with reduced communication of information between the cerebral hemispheres (Bennett et al 2010; Ota et al, 2006), with the relationship of the splenium found by Mori et al (2005) and mean FA values seen in this study. It is not unreasonable to think that these WM tracts may also play some role in the differences seen in BA scores across participants. However it should be noted that the method of tractography only allows for an estimated value within a voxel connected to a specific brain region (Behrens, 2003) and so any areas highlighted, should be considered as being most likely involved, rather than determining an exact relationship.

As already suggested to, this relationship though was too small to be detected by the limited number of participants tested, so further research on the dynamics of the relationship and potentially significant WM areas is therefore required. If replicated though, future studies should try to gain a larger sample and have them undergo the imaging process before completing the task; rather than obtaining participants from those which DTI images already existed for. This may then allow for an increased potential in finding a significant relationship between WM and BA.

A further weakness and improvement for next time regards the normality of BA scores, which indicated that scores were not typical of a normal distribution. If replicated, it would be beneficial to transform the participants BA scores to allow for the correction of distributional problems such as positive kurtosis, before then completing a linear regression analysis via the use of a log transformation in SPSS. Following this, data would convey a more normally distributed relationship, in which potentially two subpopulations may exist. If this is the case, a (un-paired) T-test could be run when regressing the behavioural data (BA scores) to the obtained DTI images. In order to split the two subpopulations, it would be advisable to either take the lower or upper third or alternatively apply a split down the middle. Scores then obtained could be compared against structural brain differences regarding each subpopulation before being compared for a difference, rather than as a whole.

Additionally, although the measure of FA is seen as being an adequate measure for

many applications and is receptive to a wide range of conditions, the tensors full shape cannot be completely described (Alexander et al, 2007), potential improvements could be made. FA is argued to be lacking in its ability to truly characterise changes in tissue (Alexander et al 2007). WM neuropathology for example, can cause the anisotropy to decrease, resulting from parallel diffusivity or increases in perpendicular diffusivity (Alexander et al 2007). Thus, FA should be used with the combination of other methods like Mean Diffusivity (MD) which can allow for a more specific WM relationship to be gathered and a better understanding as to how the diffusion tensor changes regarding a specified region (Alexander et al 2007). Due to time constraints though, this experimental research only focused on measuring FA as a basis of WM changes between individuals. Overall this would allow for a richer investigation regarding localised microstructures which may change across individuals such as with BA scores specified within this experimental study.

Finally, regarding the running of the experiment, participants did not always have the same experience. One participant conducted the study in a separate room whereby the experiment was conducted on a laptop, compared to the other 20 participants whom completed the experiment within a laboratory setting. In addition the laboratory rooms ranged in terms of size and the number of people being present during testing. Although the effects of these differing test conditions is unlikely to have had an effect on the participants, and due to controlling of image distortions during the analysis process through eddy correction, it is worth future studies trying to ensure that all participants are tested within the same environment and through the use of the same experimental equipment.

In summary, this study agrees with the opinions that tractography can permit the mapping of different WM pathways within the brain and that of the CC, in order to then study their later structural relevance. It did however not show a clear relationship between interindividual differences of WM pathways associated with the BA effect, with no tracts being measured as significant. The study though does permit the continued questioning as to whether underlying WM may affect bilateral performance, since the suggestion gained through a near significance value being found for certain WM areas is present. Additionally, the potential reason for the variability of these potential structures should be looked at since the method employed within this study gives no explanation to the underlying relationship.

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