

Durham E-Theses

Trunk and Hand-Centred Spatial Coordinate Frames

KIRSTEN NICOLE CRANE

How to cite:

CRANE, KIRSTEN NICOLE (2018) Trunk and Hand-Centred Spatial Coordinate Frames. Masters thesis, Durham University.

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a <https://etheses.durham.ac.uk/id/eprint/12581/> is made to the metadata record in Durham E-Theses
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full Durham E-Theses policy](#) for further details.

Trunk and Hand-Centred Spatial Coordinate Frames

Kirsten N. Crane

Abstract

Neurons in early visual cortex represent space within a retinocentric coordinate frame, whereas downstream in motor cortex object location is coded with respect to the effector. The reference frame used by parietal neurons for the spatial analysis required to create movement plans is still contested. One dominant view is that parietal neurons use a retinal-centred reference frame at the single-cell level, but that other coordinate schemes can be ‘read out’ when information is pooled from a population of neurons gain-modulated by the head, hand, or other body part. More recently, there has been a surge of evidence for higher-order reference frames existing at the single-cell level, predominantly within non-human primate research. Furthermore, the range of coding typologies appears to be wide and complex, with the emergence of hybrid and dimension dependent response profiles. The research presented here investigates explicit body-centred and hand-centred coordinate systems in a two-part study using a memory-guided saccade paradigm. In the neuroimaging experiment, time-series analysis was used to test for the reorganisation of topographic maps along the intraparietal sulcus (IPS), following left and right, and near and far changes to hand position. In the behavioural experiment, eye-tracking data from the right eye was used to test for differences in error, following 90° torso rotations coupled with left and right hand placements. In both experiments, the retinal coordinates of saccade targets remained constant, and significant differences between conditions would provide evidence for the contribution of hand and body-centred spatial coding. This evidence would support the recently emerging evidence from the non-human primate literature and strengthen the argument for using posterior parietal cortex (PPC) as the source of command signals for the real-time control of neural prosthetics.



Durham
University

Title: Trunk and Hand-Centred Spatial Coordinate Frames
Author: Kirsten Nicole Crane
Qualification: Master's by Research
Department: Department of Psychology
Submission Date: September 2017

Table of Contents

Introduction	4
The Receptive Field	4
The Gain Field Hypothesis	5
Evidence for Higher Order Reference Frames in the PPC	9
Behavioural Research and Spatial Reference Frames	12
Neuropsychology and Spatial Reference Frames	12
Functional MRI and Spatial Reference Frames	13
The Present Study	15
Aims and Hypotheses	18
Experiment 1 – Functional MRI	19
Method	19
Subjects	19
Saccadotopy Method	19
Conditions	20
Procedure	21
Data Acquisition	22
Data Analysis	22
Results	25
Colour Maps	25
Rose Plots	26
Statistics	26
Discussion	33
Experiment 2 - Eye Tracking	36
Method	36
Subjects	36
Conditions	36
Procedure	37
Data Analysis	39
Results	41
Amplitude Error	41
Angular Error	44
Cartesian Error	45
Reaction Time	47
Discussion	50
Future Research	56
Functional MRI	56
Eye Tracking	57
Implications	58
Summary	59

Statement of Copyright

“The copyright of this thesis rests with the author. No quotation from it should be published without the author's prior written consent and information derived from it should be acknowledged.”

Acknowledgements

As well as the much-appreciated guidance from my supervisor, Dr Jason Connolly, I would like to acknowledge the help of MRes student Joshua Podmore, for working with me on refining and debugging the Matlab scripts for the eye-tracking analysis, and PhD student Alessia Cacace, for always sharing anything she came across whilst working on the same fMRI analysis.

1. Introduction

To move around and interact effectively with the environment, the brain must perform an enormous amount of spatial processing. Even a very “simple” action, such as taking a drink from a coffee mug, requires that object location that is initially coded relative to the retina must then be coded with respect to the hand, such that an accurate reaching movement can be generated, and then with respect to the face, when directing the mug toward the lips. The brain therefore has to use a multitude of coordinate frames (or frames of reference), based first on the topographic mapping of the sensory surface (see Fishman, 1997) and later on the action effector (Brozzoli, Gentile, & Ehrsson, 2012; Fogassi et al., 1992; Graziano, Yap, & Gross, 1994; Pesaran, Nelson, & Andersen, 2006). The types of coordinate frames used intermediately by neurons in parietal cortex remain contested. Recent non-human primate research has challenged the dominant position of retinal-only coding in PPC. This has prompted new questions with regard to human spatial processing. The challenge for neuroscience is to develop non-invasive techniques that allow us to search for explicit non-retinal coordinate frames in *human* PPC. Understanding spatial processing in human parietal cortex is particularly important for brain machine interface (BMI) research because the parietal cortex is now a candidate for the control of neural prostheses (Aflalo et al., 2015; Andersen, Hwang, & Mulliken, 2010; Hauschild, Mulliken, Fineman, Loeb, & Andersen, 2012; Hwang & Andersen, 2009; Mulliken, Musallam, & Andersen, 2008; Shenoy et al., 2003).

The Receptive Field

Neurons that are spatially tuned are selectively responsive to a stimulus falling within a particular region of space. This region of space can be referred to as the neuron’s receptive field; an area that is maximally responsive when stimulated at its centre and gradually less responsive toward the perimeter (Hubel & Wiesel, 1962). The location of a receptive field in space is not absolute but anchored to some egocentric point on the body or allocentric point in external space. For example, if a neuron were using a head-centred reference frame, then any shift in the position of the head would create an equal shift in the position of the receptive field. In sensory cortex, space is coded for in the coordinates of the sensory epithelia. Neurons in early visual cortex have a retinal-centred reference frame, since the location of a visual stimulus, relative to fixation, can be derived from the pattern of light stimulation on the retina. Similarly, neurons in auditory cortex have a head-centred reference frame, since object location in head-centred coordinates can be derived from

auditory stimuli using monaural spectral cues, interaural level and interaural difference cues (Middlebrooks & Green, 1991). The term ‘retinal-centred’ is often used interchangeably with ‘eye-centred’ and ‘gaze-centred’, since moving the eyes or shifting gaze in turn affects fixation. Note, however, that these terms can be used to mean something subtly different. For example, eye or gaze-centred could be used to describe a cell that is selectively responsive to the gaze angle itself (position of the eyes within the orbits) or a particular eye-movement trajectory (Cohen & Andersen, 2002).

The above spatial coding typologies may be sufficient in sensory cortex but downstream in motor cortex there is a need for objects to be represented with respect to the effector, such as the hand in the case of reaching movements. This allows for the computation of motor error vectors used to update movement trajectories. Therefore, at some point between sensory input and motor output, space, or at least peripersonal space (the region of space immediately within reaching distance), must be represented in an effector-specific fashion. The parietal lobe, situated between the frontal and occipital lobes, receives input from sensory cortex and feeds forward to motor cortex, and is therefore in a prime location to perform the operations necessary for changes in spatial representation. One of its two functional zones, PPC, is responsible for the visual guidance of movements, movement planning, spatial attention, the manipulation of objects (both real and mental) and even quasi-spatial processes such as arithmetic and reading (Critchley, 1953). A growing body of work within the spatial processing literature has been dedicated to the question of how neurons within various sub-regions of PPC code for peripersonal space (Andersen, 1995; Andersen, Snyder, Li, & Stricanne, 1993; Colby, 1998; Graziano & Gross, 1998; Snyder, 2000).

The Gain Field Hypothesis

For well over two decades, gain field theory has dominated this literature. In 1983, Andersen and Mountcastle reported evidence for a modulating effect of gaze angle on the response of visual parietal neurons. Some of the neurons were affected by changes in gaze angle along the vertical meridian and some by changes along the horizontal meridian. In all cases, the effect was most often on response amplitude and not response selectivity; activity increased but the receptive field of the neuron remained aligned with a retinal-centred reference frame. The amplitude (or gain) of a neuron increased, on average, by 3.65% for every degree of change in gaze angle, and was observed in 44 of the 72 tested visual neurons (although only in the presence of directed visual attention) (Andersen &

Mountcastle, 1983). Some neurons were only tested along a single meridian, or within a small deviation from central fixation, and so the actual percentage was suspected to be higher. Andersen, Essick, and Siegel (1985) recorded the activity of single cells in area 7a of the rhesus monkey in response to a light stimulus presented at the same retinotopic location but relative to nine different fixation positions. They, again, observed how changes to the angle of gaze caused systematic changes to the magnitude of the neuronal response. Since their discovery, neurons with gain fields have been observed in many cortical areas and thus gain modulation appears to be a widespread mechanism for integration (for a review, refer to Salinas and Sejnowski (2001)).

Although each modulated neuron carries some information on both the position of the eyes within the orbits and the position of the target in retinal coordinates, the information from a single neuron is not enough to 'read out' the location of a target with respect to the head (Boussaoud & Bremmer, 1999). Information must be pooled across a population of neurons so that the population code (Pouget, Dayan, & Zemel, 2000) represents locations in an eye position-dependent head-centred coordinate space. The process of pooling information across a population of neurons is non-linear, that is, the inputs are not simply added or subtracted. In fact, as a result of recurrent connections, whereby similarly tuned neurons excite each other and differently tuned neurons inhibit each other, gain modulation is very close to multiplicative (Salinas & Abbott, 1996). It has been put forward that information concerning the position of the eyes within the orbits is obtained from proprioceptive input (Dijkerman & de Haan, 2007) or corollary discharge (Wurtz, 2008). Furthermore, the position of the eyes is not the only found modulator of PPC neural activity, with evidence for visual neurons that are gain-modulated by the position of the head (Brotchie, Andersen, Snyder, & Goodman, 1995) and other body parts. Information concerning head position can be obtained from neck proprioceptive signals (Brotchie et al., 1995), vestibular signals (Snyder, Brotchie, & Andersen, 1993), landmark or optic flow information (Andersen, Snyder, Bradley, & Xing, 1997).

Given the widespread existence of gain modulation and the evidence for various modulating factors, the proposition has been put forward that retinal-centred coding is all that is needed by single visual neurons in PPC for the spatial analysis required to create movement plans. Information can be combined in a serial manner, each time producing a population code with a different reference frame; retinal coordinates can be combined with eye position to read out craniotopic coordinates, craniotopic coordinates can be combined with head position to read out body-centred coordinates, and so forth (Batista, Buneo,

Snyder, & Andersen, 1999). In the same way, information can be subtracted out, for example, auditory neurons that encode targets in head-centred coordinates can be gain-modulated by eye position so that the location of a target in retinal-centred coordinates can be derived at the population level (Cohen & Andersen, 2002; Stricanne, Andersen, & Mazzoni, 1996). Furthermore, gain modulation has been put forward as the mechanism for coordinate *transformations*, allowing for an eye position-independent response in downstream motor neurons. Zipser and Andersen (1988) used back-propagation learning to train a three-layer neural network model to map visual targets to head-centred coordinates, given arbitrary pairs of eye and retinal positions. They found the middle-layer ‘cells’ developed gain fields similar to those observed in PPC.

The above population-coding hypothesis argues that, within PPC, higher-order reference frames (coordinate schemes with a reference point ‘beyond the retina’) can only be achieved at the population level. This view is supported by a multitude of studies that present evidence for retinal-centred coding in PPC. Often, the paradigm used to differentiate coordinate schemes is one whereby a pointing or saccade target is, for one condition, held constant in head/body/hand coordinates but altered in retinal coordinates, and for the second condition, held constant in retinal coordinates but altered in head/body/hand coordinates. Note that, commonly, a manuscript might refer to all reference frames beyond the retina under one umbrella term, since the methodology is unable to differentiate between specific higher-order coordinate schemes if all body parts other than the eye remain in the same position across testing. Examples of alternative paradigms include the use of reversing prisms (Fernandez-Ruiz, Goltz, DeSouza, Vilis, & Crawford, 2007), a double-step paradigm involving intervening saccades (Medendorp, Goltz, Vilis, & Crawford, 2003), and a repetition suppression paradigm (Van Pelt, Toni, Diedrichsen, & Medendorp, 2010).

The 1999 study by Batista and colleagues provides a good example of the typically used paradigm. In this study, single-cell recordings were taken from monkey parietal reach region (PRR) as they performed non-foveated reaches towards light emitting diode (LED) targets. In two of the conditions, reaches were made from the same initial hand position but at different fixation positions. In the remaining two conditions, reaches were made at the same fixation position but from different initial hand positions. Within these condition pairs, the authors performed a correlation analysis on the resulting tuning curves. Using the correlation value from the pair at the same retinal location as the x-coordinate, and the correlation value from the pair at the same hand-centred location as the y-coordinate, the

results of the analysis were plotted for all 74 neurons. They found that 84% of neurons fell below the line of equal correlation, meaning that the tuning properties of these neurons were more consistent with a retinal-centred coordinate scheme. When the same paradigm was used to test non-human primate PRR with auditory stimuli, again, significantly more neurons were more heavily influenced by eye position than hand position (Cohen & Andersen, 2000). This is arguably a counterintuitive result, implying that even neurons with reference frames further forward in the visuomotor transformation process (e.g. auditory targets encoded in a head-centred reference frame) are brought into an oculocentric frame, despite ultimately needing to represent object location with respect to the reaching arm. The lateral intraparietal region (LIP), primarily responsible for saccade activity, would also appear to use oculocentric spatial representations, perhaps less surprisingly. The evidence for this from single-cell recording is supported by research using microstimulation (Constantin, Wang, Martinez-Trujillo, & Crawford, 2007). These authors report that the endpoints of stimulation-evoked gaze-shifts were most convergent when plotted in eye coordinates, with initial gaze direction appearing to modulate the *likelihood* of a gaze shift (a possible reflection of gain field activity).

Batista et al. (1999) propose some advantages to using a retinal-centred reference frame for movement planning in PPC. They suggest it might facilitate hand-eye coordination, reduce the computational load (by not having to transform everything in a visual scene into limb coordinates), and, since the hand is usually visible during reaching, they suggest it might be ‘parsimonious’ if on-line corrections to the movement plan are in the same coordinates as the visual error signals. Another advantage to the widespread use of retinal-centred coding is the provision of a common reference frame to facilitate multisensory integration, as has been reported in the superior colliculus (Jay & Sparks, 1987) and frontal eye fields (Russo & Bruce, 1994). There is, however, a fundamental flaw to using a retinal-centred frame of reference for movement planning. That is, every time the eyes move, the spatial registry between the retina and the environment alters, and, since we make approximately three eye movements a second (Schwartz & Krantz, 2014), there is the potential for this to occur in-between planning and execution. To resolve this problem of space constancy, it is possible that the retinal coordinates of visual memory traces are internally remapped to compensate for each eye movement (spatial updating), using outflow signals such as corollary discharge (Stark & Bridgeman, 1983) or inflow signals such as proprioception (Steinbach, 1987). There is evidence to support this notion of a dynamic retinal-centred system from numerous human and non-human primate studies, commonly using an intervening saccade paradigm (Batista et al., 1999; Fiehler, Schutz, & Henriques, 2011;

Henriques, Klier, Smith, Lowy, & Crawford, 1998; 2005; Medendorp et al., 2003; Thompson & Henriques, 2010).

Evidence for Higher Order Reference Frames in the PPC

There is, however, an alternative resolution to the space constancy problem, which is the contested view that parietal cortex uses higher-order reference frames at a single-cell level. In the literature, this group of higher-order coding typologies are often referred to as 'pure', 'real' or 'explicit'. These coordinate systems would be independent of eye movements and would therefore provide a stable encoding mechanism, without the need for spatial updating. As early as 1993, receptive field mapping in monkeys revealed 14 cells (of 120 tested) in the anterior bank of the parieto-occipital sulcus that remained active at the same spatial location across seven tested gaze directions (Galletti, Battaglini, & Fattori, 1993). Evidence for the existence of these cells in PPC does not refute the existence of gain-modulated retinocentric coding, or its role in coordinate transformations, but it does suggest that these transformations occur earlier in the brain (i.e. within PPC and not just downstream in motor cortex). In another example, Mulette-Gillman, Cohen, and Groh (2005, 2009) found a continuum of reference frames from pure retinal-centred to pure head-centred in areas LIP and MIP (medial intraparietal) of macaque monkeys, as they made saccades to both visual and auditory targets. These frames of reference were observed regardless of the time at which neurons were recorded (stimulus onset to movement initiation). Most importantly, the majority of cells were not retinal-centred but fell in the middle of such a continuum, i.e. most were using a mixed head/eye spatial coding system. Rather than this reflecting a cluster of cells, with some cells using retinal-centred frames and some using head-centred frames, Mulette-Gillman and colleagues discovered single cells that were using a genuine hybrid reference frame. They observed partial shifts to the centre of mass of the cell's response profile, that is, the point at which the cell was anchored represented a compromise between eye and head position. These results are mirrored in other areas of non-human primate PPC, for example, Avillac and colleagues found an eye- to head-centred continuum for visual stimuli within ventral intraparietal area (VIP), as well as reference frames that were exclusively head-centred for tactile stimuli (Avillac, Deneve, Olivier, Pouget, & Duhamel, 2005).

Furthermore, the compromise between two spatial reference frames within a mixed reference frame need not consist of equal contributions. Bosco and colleagues (Bosco, Breveglieri, Hadjidimitrakis, Galletti, & Fattori, 2016) found some cells with a hybrid reference frame whereby the two coding typologies contribute equally, which they termed

balanced cells, and some cells whereby one of the two reference frames contributed more than the other, which they termed unbalanced cells. The complexity of the tuning properties in PPC neurons is complicated even further by the discovery that some neurons only demonstrate spatial tuning along one axis, or, are spatially tuned in one reference frame for elevation and another for azimuth (Duhamel, Bremmer, Ben Hamed, & Graf, 1997). These authors also found a continuum of eye-to-head reference frames within non-human primate VIP, again with a mixed majority, but other types of hybrids have been found, including mixed eye/hand neurons (Bosco et al., 2016; Buneo, Jarvis, Batista, & Andersen, 2002) and mixed body/hand neurons (Hadjidimitrakakis, Bertozzi, Breveglieri, Fattori, & Galletti, 2014; Piserchia et al., 2017). Some authors have suggested that the hand-centred location of a target could be calculated by vectorially subtracting the location of the hand in eye coordinates from the location of the target in eye coordinates (Buneo et al., 2002; Pesaran et al., 2006). However, more recent studies (Hadjidimitrakakis et al., 2014) have performed reaching in the dark, meaning hand location must have been computed using some other source of information, such as proprioceptive signals from the moving limb or corollary discharges from motor centres. Comparing reaches made in the dark with reaches made in the light has revealed three classes of cells: motor cells not receiving any visual input, visuomotor plus cells, whereby visual and somatosensory input appeared to be additive, and visuomotor minus cells, whereby visual input appeared to impair the cell (Fattori, Breveglieri, Bosco, Gamberini, & Galletti, 2017).

These dominant mixed coding typologies could represent the intermediate stage in coordinate transformations (hence why some authors refer to this type of spatial representation as intermediate coding (Xing & Andersen, 2000)). Alternatively, it is possible that they serve some sort of purpose or are advantageous in some way. Mullette-Gillman et al. (2005) suggest that a mixed reference frame would complement the format of motor commands; most movements and interactions with objects require information about the location of an object relative to multiple reference points. It has also been suggested that mixed reference frames are what actually allow for neural circuits to perform optimal multisensory integration (Avillac et al., 2005; Pouget, Deneve, & Duhamel, 2002), as opposed to the proposition that a common reference frame is required for this process. This notion is supported by an artificial neural network model referred to as a recurrent basis function network. The basis function units in this model use partially shifting reference frames to perform multidirectional sensory predictions, such as predicting the visual location of a stimulus given its tactile location on the skin and vice versa (Neppi-Modona, Auclair, Sirigu, & Duhamel, 2004). Another (not mutually

exclusive) possibility is that mixed coding makes the whole system more flexible. The idea that a neuron can encode in multiple frames simultaneously and then possibly switch between, or become ‘unbalanced’ towards, one of the two frames depending on the action being performed, is similar to the conversion-on-demand model (Henriques et al., 1998) whereby only select neurons undergo a coordinate transformation from eye to head/body coordinates for motor execution. Given the computational complexity of coordinate transformations, this makes good economic sense. In relation to this, Bosco et al. (2016) found that the variability of coding typologies decreased with time. This greater constancy of neural discharge as the reach movement unfolds might reflect the tendency of neurons to use a mixed hand/eye reference frame initially when a target is sensed (so that they remain flexible), and then a pure hand-centred reference frame once a reach movement is intended or initiated.

There are a number of reasons for the discrepancy between those studies that report only retinal-centred coding at the single-cell level and those studies that have found evidence for higher-order coding at the single-cell level. First, the methodology of each study is different. Some methods are unable to distinguish between explicit coding and population codes; see Mullette-Gillman et al. (2009) for a pictorial explanation as to why the response patterns would look the same for a pure head-centred neuron and a pure retinal-centred neuron with an eye position gain field when the method involves single fixed retinal sampling, orthogonal slice sampling (as opposed to parallel), or best direction retinal sampling. Secondly, the type of analysis varies between studies. For example, many studies have produced a model response profile for each of the reference frames being tested. The data from a neuron is then correlated with each of the models, and the neuron is designated the reference frame belonging to the model that produces the greatest correlation. However, with the more recent understanding that neurons can have a mixed coding typology, and more importantly, an unbalanced one, it is clear how this form of analysis might misrepresent the coding properties of the cell; an unbalanced eye-centred mixed cell is going to correlate more with the eye-centred model, but it does not mean that this cell is using a purely eye-centred reference frame. Finally, there are also differences in the way studies report their results. For example, in a review by Cohen and Andersen (2002) it is reported that neurons in monkey PRR have been found to code auditory targets in retinal-centred coordinates however, the original paper states that “changes in initial hand position had only a moderate effect on the centre of mass” (Cohen & Andersen, 2000, pg. 648) and “in some neurons, eye and hand position affected PRR activity in a complex manner” (Cohen & Andersen, 2000, pg. 649). Thus, a population of neurons reported to

code in a pure retinal-centred reference frame are in fact more likely to be using an unbalanced mixed eye/hand reference frame.

Behavioural Research and Spatial Reference Frames

The evidence presented thus far has come from non-human primate research. Human research on spatial reference frames can be more challenging because of the unavailability of high spatial resolution techniques like single-cell recording and microstimulation. One option for the investigation of spatial reference frames in human PPC is behavioural research. In one example of a behavioural study, subjects pointed to a remembered central target (without visual feedback from their hand) whilst fixating either centrally, 10° left, or 10° right of centre (Pouget, Ducom, Torri, & Bavelier, 2002). Pointing error was significantly greater for left and right fixation compared to central fixation, despite the pointing target remaining in the same location in head, body and hand coordinates, and regardless of whether the target was visual, auditory, or proprioceptive. The authors concluded that target location was coded in retinal coordinates irrespective of sensory modality. Of course, results from behavioural studies are only suggestive of a particular coordinate scheme and involve a certain amount of speculation.

Neuropsychology and Spatial Reference Frames

In a similar way, neuropsychological studies can *suggest* one reference frame or another. For example, patients with unilateral neglect have trouble orienting, perceiving, and responding to the contralesional side of space, and determining the centre of this spatial deficit (what are patients neglecting one side of space relative to) has been the goal of many clinical and experimental studies. A popular model of unilateral neglect is that this causes the patient's subjective trunk midline to translate (shift laterally) towards the ipsilesional side of space (Kinsbourne, 1993). Karnath (1994) demonstrated this by asking patients to direct a laser point to the location they felt was directly straight ahead. Whereas the control group of healthy subjects could accurately point to the objective centre, patients pointed 15° to the right. Multiple studies have succeeded in alleviating the symptoms of neglect by manipulating the subjective trunk midline back toward centre via neck-muscle proprioceptive stimulation, caloric vestibular stimulation, or via physical or illusory trunk rotations (Karnath, 1994; Karnath, Christ, & Hartje, 1993; Karnath, Schenkel, & Fischer, 1991; Rubens, 1985). It ought to be possible, therefore, to induce neglect-like symptoms in healthy subjects via the same techniques however, the evidence for this has been

inconsistent, with some reporting it possible (Grubb & Reed, 2002; Hasselbach-Heitzeg & Reuter-Lorenz, 2002; Karnath, Fetter, & Dichgans, 1996) and others not (Chen & Niemeier, 2014; Rorden, Karnath, & Driver, 2001). Not all studies describe neglect within a body-centred coordinate frame; different tests and different patients have demonstrated spatial deficits centred on the eye, hand, room, or attended object (Robertson & Marshall, 1993).

Functional MRI and Spatial Reference Frames

An alternative option for human research is the use of neuroimaging, such as functional magnetic resonance imaging (or fMRI). DeSouza and colleagues (DeSouza et al., 2000) examined changes to fMRI signal intensity following manipulations to gaze direction in a memory-guided delayed pointing task. Whilst fixating 14° left or right, subjects pointed either to a central target or to retinotopically identical targets 6° either side of fixation. Although they found a significant modulation by eye position, the study did not explicitly test spatial selectivity. Finding that eye position modulates signal intensity is not enough to provide evidence for retinocentric coding, since both retinal-centred and head-centred cells with orbital gains fields have been reported (e.g. Stricanne et al. (1996)). Other spatial processing studies using fMRI have capitalised on the widespread use of topographic organisation throughout the brain. A topographic map is a point-by-point representation of the contralateral hemifield, such that adjacent points on the sensory surface activate adjacent neurons on the cortical surface, for example, retinotopic mapping in visual cortex. Maps commonly have a columnar organisation, can sometimes contain duplicate representations in multiple locations, and, particularly in higher cortical areas, can contain ipsilateral as well as contralateral representations (although the contralateral hemifield is often still overrepresented). Topographic organisation need not be linked to a sensory surface; maps can be spatiotopic, such as saccadotopic maps that represent saccade endpoints in space (Serenio, Pitzalis, & Martinez, 2001), or linked to an effector system, such as the topographic organisation of saccade amplitude in the frontal eye fields (FEF)(Bruce & Goldberg, 1985). In fact, action-related tasks have revealed a multitude of maps within parietal cortex that were not previously revealed using visual mapping techniques such as the flickering checker-board stimuli in retinotopy.

One way in which neuroimaging studies can use these maps is by taking advantage of the well-known contralateral bias (the overrepresentation of the contralateral hemifield). For example, in a memory-guided delayed movement task using both saccades and pointing, Medendorp et al. (2003) identified contralateral topographic zones in regions considered to

be human analogues of primate LIP and PRR. Crucially, these authors introduced an intervening saccade that caused the static target to switch sides with respect to fixation, but not with respect to the head or body midline. The authors reported an exchange of activity across hemispheres that led them to believe these regions represent space in a retinocentric frame. Utilising the existence of topographic maps can be taken even further with the use of phase encoding techniques. Upon systematically changing the polar angle of a stimulus through 360° , the task (be it passive like retinotopy, or movement-based like saccadotopy) can systematically activate populations of neurons across the ordered projections of any existing maps, creating a wave of activity for each mapped voxel with the same periodicity as the stimulus cycle and a peak time-locked to the target that produced the greatest response, i.e. the region of visual field spatially represented by the underlying neurons. Sereno et al. (2001) were the first to adopt this technique within a memory-guided saccade paradigm. Subjects made delayed saccades to the remembered location of visual targets presented at twelve 30° intervals. For all twelve subjects, the task revealed robust mapping in two bilateral regions, with remarkable within-subject consistency across days and different versions of the task. One of the two identified regions, midway up the IPS, potentially corresponds to area LIP, known for its saccadic activity in non-human primates (Gnadt, Andersen, & Blatt, 1986). Note that whereas macaque LIP is on the lateral bank of the IPS, the human homologue is somewhat medial to it.

Similar studies have been conducted since (Konen & Kastner, 2008; Schluppeck, Glimcher, & Heeger, 2005), finding as many as six topographic maps within PPC. However, without moving the position of the eyes or other body part, this centre-out movement paradigm is unable to differentiate between retinal and nonretinal coordinate frames. Pertzov, Avidan, and Zohary (2011) adopted a diamond-shape fMRI paradigm with eight conditions in total (saccades to and from the four points of the diamond). In this way, they could then compare saccades with the same movement trajectory but different endpoint, and saccades with the same endpoint but different movement trajectory. Response patterns for same-trajectory saccades were correlated in the FEF and IPS, indicating retinal-centred coding, however, response patterns for same-endpoint saccades were correlated in middle IPS, even when the movement trajectory was different. These findings provide evidence for representations in (at least) a head-centred frame. Sereno and Huang (2006) also reported evidence for head-centred representations via fMRI. In this experiment, the authors used a video stimulus played within a circular aperture and had subjects track a fixation cross in the centre of the aperture as it moved periodically with respect to the face. Alternatively, Connolly, Vuong, and Thiele (2015) retained the same

saccadotopy paradigm used by Sereno in 2001, but had subjects perform the task from a left, centre and right fixation cross, so that saccade targets remained identical in retinal coordinates but differed with respect to the head/body midline. As had been done previously, Connolly et al. (2015) used phase values to characterise (in the temporal domain) the wave of activity produced by each voxel in response to the task. However, with using more than one fixation point, they were also able to assess the effect of changing target location in head/body coordinates by calculating a *mean* phase value for a defined region of interest and comparing between conditions. Significant differences were found in more than one region along the IPS, indicating that these topographic maps had ‘reorganised’ i.e. there was a change to the spatial selectivity of underlying neurons for at least some of the voxels within the map. Target location remained constant in retinal coordinates, and a gain modulation by eye position would only affect the amplitude of activity, not the region of space being represented, therefore the authors presented this as first evidence for extensive higher-order spatial representation in human PPC.

Continuing on from this work, Connolly and a new team (Connolly, Podmore, Kentridge, & Cavina-Pratesi, in preparation) adopted the same paradigm and analysis but with a body orientation manipulation. A custom-built rotating scanner bed meant subjects could perform the task from a central gaze position, whilst their torso was oriented 20° left, 20° right, or at centre. Again, the authors found significant differences in the mean phase value between conditions, providing evidence for higher-order representation. The results were most striking for the left hemisphere, with the mean phase value undergoing more or less a 180° inversion between torso left and torso right. Whereas the 2015 study was able to differentiate between eye and head-centred reference frames, but not head and body-centred, this later study was able to differentiate between head and body-centred reference frames, but not body and hand-centred. The next logical step in this stream of investigatory work, therefore, was to manipulate hand position within the same paradigm.

The Present Study

In the present study, subjects performed the same memory-guided saccade task in the scanner with their right hand at one of four positions, including two lateral positions (left and right) and two depth positions (near and far). The static hand positions involved gripping the rung of a two-tier ladder-like apparatus, such that the two depth positions were above and below each other in the vertical domain. The two depth positions were organised in this way because subjects completed the task in the supine position, and since

we define depth as distance perpendicular from the torso, a change in depth translates as ‘up’ instead of ‘out’. The region of interest (ROI) in this study wrapped around the length of the IPS, from the postcentral sulcus to the parieto-occipital sulcus, and included both the voxels within the sulcus and a portion of the lateral surface surrounding the sulcus. For the paradigm to be made possible, it was crucial for the ROI to contain topographic organisation, and since there is evidence for a band of topographic organisation along the IPS (Konen & Kastner, 2008), we thought it sensible to wrap around this entire area, especially seen as topographic maps can differ in form and location between subjects (Sereno et al., 2001). Exploring more than one functionally defined region was appropriate for this initial investigation, given that there was little in the literature to suggest where we might find pure hand-centred cells within human PPC.

To our knowledge, this is the first attempt to manipulate hand position in the scanner, for the purpose of investigating spatial coordinate frames in human PPC. Furthermore, this is also the first *human* study, to our knowledge, to test coordinate frames in the depth dimension. Even within the non-human primate literature, only a handful of single-cell recording studies have ventured into the midsagittal plane. This handful of studies have all adopted a similar paradigm; the monkey sits upright and reaches towards one of nine LED targets presented at eye level in three rows of three (left, right, centre; near, intermediate, far), from one of two initial hand positions at waist level (near, far). Taken together, the results from these studies have illuminated a caudal-rostral gradient, or gradual increase, in the contribution of hand-centred coding as spatial processing proceeds anteriorly through parietal cortex toward motor cortex; in caudal area V6A the majority of neurons had a body-centred reference frame (Hadjidimitrakis et al., 2014), in the intermediate area PEc the majority of neurons had a mixed body/hand reference frame (Piserchia et al., 2017), and in rostral area PE (area 5) the majority of neurons had a pure hand-centred reference frame (Ferraina et al., 2009). Since targets were foveated, it was not possible to distinguish between body, head, and eye-centred reference frames in these studies. When the fixation point and reaching target have been decoupled, neurons in V6A have been found to code either in eye or mixed eye-hand reference frames (Bosco et al., 2016). There would also appear to be a caudal-rostral *decrease* in depth tuning (as opposed to directional tuning (Hadjidimitrakis, Dal Bo, Breveglieri, Galletti, & Fattori, 2015)). These findings are complementary considering that eye-centred coding has been found to have greater depth-sensitivity, and hand-centred coding, greater directional sensitivity. Bosco et al. (2016) have suggested that this is because depth is processed later with respect to direction, and so

neurons with directional tuning may have already transformed from eye-centred into hand-centred, whereas neurons with depth tuning might not yet have transformed.

The expense of scanning restricted the fMRI experiment in the present study to two subjects. We therefore designed a second full-scale behavioural experiment that we felt was complementary to the fMRI work, and the work of others within the lab. In the behavioural experiment, ten subjects completed the memory-guided saccade task in six different positions, all of which included a hand placement (left or right) and a torso orientation (90° left, centre or 90° right). Eye tracking was used to calculate four measures of performance (amplitude error, angular error, Cartesian error and reaction time) and mean scores were compared between conditions. The same experiment, minus the hand manipulation, was conducted by a lab colleague just two years earlier, with six participants and 20° rotations. Podmore (2015, dissertation) describes increased saccade ‘quality’ (lower error scores and faster reaction times) for targets ipsilateral to torso rotation. Although the study yielded non-significant results, the effect sizes were often large, indicating the possibility of unearthing a significant effect with more participants and/or a larger rotation.

Paschke, Kagan, Wustenberg, Bahr, and Wilke (2015) did include the hand in their trunk rotation study, but with respect to handedness and not hand position. These authors used a temporal order judgement (TOJ) task, which involved presenting two stimuli, one in left and one in right hemifield, at various stimulus onset asynchronies (SOA), and asking participants to make a saccade to the stimulus that appeared first. They then measured the minimum SOA required in order for: a) a stimulus to be reliably discriminated as appearing first (just noticeable difference, JND), b) a stimulus to be *perceived* as appearing first more than 75% of the time (the 75% threshold), and c) the subject to *perceive* stimulus presentation as simultaneous (point of subjective simultaneity, PSS). All of these measures equate to having or not having a prior entry bias for one side of space. For example, neglect patients have an ipsilesional prior entry bias reflected in a 200ms PSS (Ro, Rorden, Driver, & Rafal, 2001). In the torso centre condition, they reported a significant right sided prior entry bias for right handers, but no left sided bias for left handers, and no significant difference between handedness groups. They did find a significant difference in PSS between left and right-eye dominance groups, however, with left-eye dominant subjects presenting a leftward bias and right-eye dominant subjects presenting a rightward bias. In addition, they found a main effect of trunk orientation in left (but not right) handers, with rightward rotations causing a significant rightward bias and leftward rotations causing a

non-significant leftward bias. The only significant finding for right handers was a lowering of the 75% threshold for right stimuli following a rightward rotation. In a different version of the experiment, subjects indicated their temporal judgement by making a saccade to an incongruent upper or lower screen location. No trunk-rotation induced biases were found in this version of the task, and so the authors concluded that trunk rotation had a motor and not a perceptual effect.

Aims and Hypotheses

The aim of both experiments in the present study was to test for pure nonretinal coordinate frames in the healthy human. In the fMRI experiment, we specifically investigated hand-centred coordinate frames along and within the IPS. The present study was an extension of work by Connolly and colleagues (2015), using the same paradigm to test a different, more specific representation (the hand, as opposed to the head and body) and in more than one dimension (making both horizontal and vertical changes to hand position). The evidence for some neurons using a different reference frame along different axes makes it important to test in more than one dimension. If hand-centred representations exist within this region, either for depth or direction, we would expect to see a significant difference in mean phase between conditions. This is because if any one voxel contains neurons with a hand-centred reference frame, then the region of absolute space represented by these neurons will change with each position of the hand, meaning that the target eliciting the greatest response will also change. In the behavioural experiment, both body-centred and hand-centred coordinated frames were investigated simultaneously. Torso position was manipulated in addition to hand position because previous work had indicated, but not successfully demonstrated, a significant effect of torso rotation within this paradigm. In line with the suggestions made by the author of this study, both participant numbers and the degree of rotation were increased. We expected to see the same results, with an increase in saccade quality for targets ipsilateral to rotation, at least for rightward rotations; the prior entry bias found by Paschke et al. (2015) was only significant for right targets following rightward rotation, and the reduced error for ipsilateral targets in the Podmore (2015) study was only significantly lower than the error for the opposite visual field at torso right. The added research question was whether a hand position manipulation would have a similar effect, and if so, whether the effects would be additive, with error and reaction time for right visual field targets at its lowest when both the torso and hand were to the right, for example.

2. Experiment 1 – Functional MRI

Method

Subjects

Two postgraduate research students (one male) were recruited for the fMRI experiment. Both subjects were right-handed, over eighteen years of age ($M = 24$ years), had no history of neurological defects and had normal vision.

Saccadotopy Method

Saccadotopy, like retinotopy, is a phase encoding technique, which systematically changes the polar angle of saccade endpoints in target space. So that there is no potential visual stimulation, saccades are directed towards remembered target locations and not physical targets. The saccadotopy paradigm used in this study is the same memory-guided delayed saccade task outlined by Sereno et al. (2001). At the start of every trial, subjects fixated on a white cross in the centre of a black screen. Whilst fixation was maintained, a target (a high contrast, 0.22° white dot) appeared in the subject's periphery for 250 milliseconds (ms). Following target presentation, one hundred target-sized dots were presented throughout a 3-second delay period. These distracter dots formed an annulus with an inner radius of 5° and an outer radius of 10.4° , relative to the central cross. Offset of the distracter dots, as well as dimming of the fixation cross, cued subjects to make a saccade to the remembered location of the target and back to centre as quickly as possible (within 250ms). The central fixation cross then brightened in preparation for the next target. The total time between successive target onsets was 4.5 seconds.

Targets appeared at one of twelve possible locations, spaced 30° apart around an invisible circle (with a radius of 7.7°) much like the numbers on a clock face. The exact polar angle and eccentricity of targets was staggered within 2.5° of visual angle on both axes so that the location of targets could not be accurately pre-empted. Even so, target eccentricity remained within the range of eccentricities covered by the band of randomly distributed distracter dots. The presentation of targets was stepped in an 'around the clock' fashion so that successive targets advanced through the twelve target locations in either a clockwise (CW) or a counter clockwise (CCW) direction. **Figure 1** illustrates the stages of the paradigm.

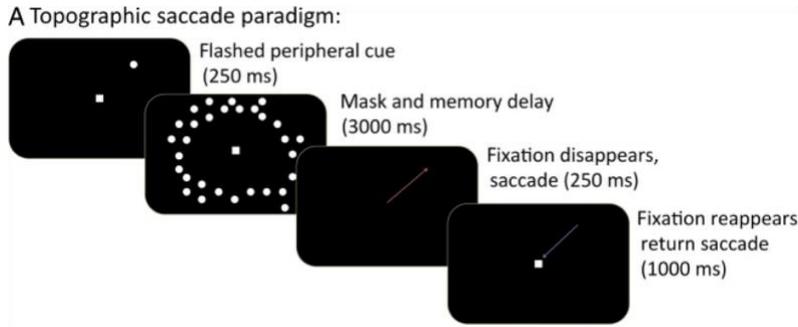


Figure 1. Stages of the memory-guided saccade task. Adapted with permission from “Gaze-Dependent Topography in Human Posterior Parietal Cortex”, by J.D.Connolly, 2015, *Cerebral Cortex*, 25(6), pg. 1520.

Conditions

The purpose-built apparatus slotted into the scanner bed at whichever point was most comfortable for the subject to assume the four required hand positions. The apparatus, as illustrated in **Figure 2**, consisted of two horizontal bars, one above the other. Subjects grasped and held onto the bottom bar (20cm from the scanner bed and approximately 5cm from the torso) for ‘near’ conditions and the top bar (33cm from the scanner bed and approximately 18cm from the torso) for ‘far’ conditions. Taped markers allowed subjects to feel for where along the bar to grasp, helping toward consistency within conditions. There were two marked positions on each bar, one leftward of the midline and one rightward. This created four positions in total: near left, near right, far left and far right (see **Figure 2B**).

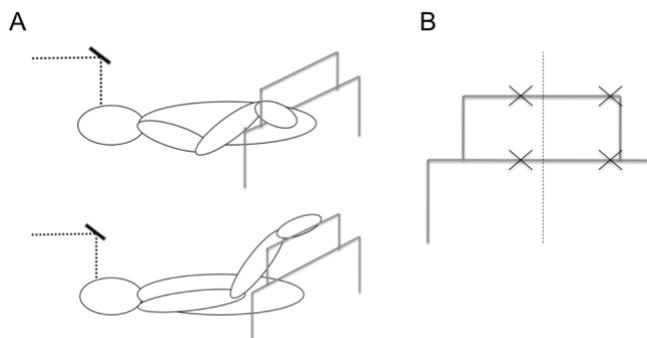


Figure 2. (A) The subject in the supine position with the apparatus placed over the body at approximately waist level. (B) The four hand positions on the apparatus: (clockwise from top left) far left, far right, near right, and near left.

All hand positions were made with the subject’s right hand. For this reason, the leftward (or contralateral) hand positions were closer to the midline than the rightward (or

ipsilateral) hand positions, to prevent excessive stretching and muscle tension as subjects reached across their body. Prior to scanning, each position was tested for the required duration to check for any potential discomfort. It is important to note that these positions were static hand positions; subjects did not reach toward these positions, or make any movements during scanning. The study employed a within-subjects design, with each subject completing the saccadotopy paradigm at *all four* hand positions.

Procedure

The potential subjects were handed an invitation letter (**Appendix A**), which briefly outlined the purpose of the study, the duration and the location of the experiment. If the individuals were agreeable to proceed they were each provided with a participant information sheet (**Appendix B**) providing more detail on the study procedure, any involved risks, and a list of potential discomforts, such as loud noise or feelings of claustrophobia. In addition, subjects were made aware of their right to withdraw at any time, without reason and without repercussions, and of the means by which data would be kept confidential (anonymous computer files, locked filing cabinets, and the storing of names and addresses separate to other data). If the individual agreed to participate, they were asked to complete the Durham University general consent form (**Appendix C**), the South Tees Hospital NHS Trust and Durham University MRI consent form (**Appendix D**), and the South Tees Hospital NHS Trust and Durham University MRI screening form (**Appendix E**). In addition, an information sheet for first-time fMRI participants was given to subjects to take home and refer to on the morning of their scanning session (**Appendix F**).

On arrival at the James Cook University Hospital, subjects were reminded of the task and of MRI health and safety before being taken into the scanning room and positioned for testing. Subjects lay supine within the scanner, with their head supported by soft, flexible foam pads to minimise any head movement. Foam earplugs were provided to minimise discomfort due to scanner noise. A mirror was attached to the head coil approximately 10cm from the subject's face and angled so that subjects could comfortably view the whole screen at the rear of the scanner by looking straight ahead. A 24 inch and MRI compatible Canon XEED LCD projector (60Hz, 1920 x 1200 pixels) was used to project the stimuli onto the screen and Psychtoolbox controlled stimulus presentation within Matlab.

Subjects completed twelve runs of the saccadotopy (three runs per position), with hand position being altered after every run. Saccades to each of the twelve locations constituted a cycle and subjects completed five cycles per run. In this experiment, the presentation of targets was stepped in a counter clockwise (CCW) as well as a clockwise (CW) direction. Successive runs alternated between CW and CCW. For one of the sessions, the first run was conducted at ‘far left’ and hand position was altered in a clockwise fashion (far left followed by far right, near right, and near left). For the other session, the subject’s hand moved through the four positions in a counter clockwise fashion. The scanner intercom was used to remind subjects of which hand position to assume before each run of the saccadotopy.

Data Acquisition

Functional MRI data was collected using a Siemens Tim Trio 3-Tesla MR scanner and a 32-channel head coil. A single scanning session involved twelve functional scans (one per saccadotopy run) followed by a T1-weighted anatomical scan and, for alignment purposes, an in-plane anatomical scan in the same slice orientation as the functional scans. This roughly equated to 1 hour and 15 minutes in the scanner. For each functional scan, we collected 180 functional volumes of whole-brain T2*-weighted echo-planar scans with the following parameters: TR = 1.5; TE = 30 ms; field of view = 192mm²; voxel size = 3 mm³; flip angle = 75°, matrix size = 64x64x30; 30 coronal slices with 3 mm thickness.

Data Analysis

The data from this experiment was analysed using the open source software mrTools (gru.stanford.edu/doku.php/mrtools/overview) in Matlab R2015b (MathWorks, Massachusetts, US). Each functional scan was labelled as either ‘CW’ or ‘CCW’, with the total number of frames set to 180 and the number of junk frames set to zero. In mrAlign, we aligned the inplane anatomical volumes to the T1-weighted anatomical volumes, before aligning the T2*-weighted functional scans to the inplane. One subject required a manual translation adjustment of -6 (downward).

Before running the correlation analysis, CW runs and time-reversed CCW runs were averaged together. The more averaging that can be done, the higher the signal-to-noise-ratio (SNR). A limited amount of time in the scanner meant we could only collect data for three runs at each of the four positions. Therefore, rather than comparing the four different

hand positions and averaging across three runs, we decided to do two sets of comparisons: left with right and near with far. This allowed us to average across six runs. It also allowed us to dissociate the effect of changing the hand's position in the depth dimension from the effect of changing the hand's position along the horizontal axis of the frontal plane. Averaging together CW runs with an equal number of time-reversed CCW runs also addressed the issue of hemodynamic lag. It takes approximately four to six seconds for the vascular system to respond to the brain's need for glucose, therefore the time measurements for recorded activity would be several seconds too late with respect to the actual timing of the neuronal event. However, when CCW runs are time reversed, the time measurements for recorded activity become several seconds too early and therefore, when CW and CCW runs are averaged together, the effect of the hemodynamic lag is cancelled out.

The subsequent correlation analysis computed coherence and phase values for every voxel. **Figure 3** provides an example of a single voxel's average time series, with time in seconds on the x-axis and the percentage of signal change on the y-axis. As can be seen, the raw data is overlaid by a best fitting sinusoid curve at the same 54-second periodicity. The coherence values that mrTools computes (ranging from 0 to 1) are a measure of association between this reference waveform and the raw signal, with a value of 1 indicating a perfect fit. Coherence is essentially the time series analogue of the correlation coefficient, but taking into account lead, lag, and smoothing.

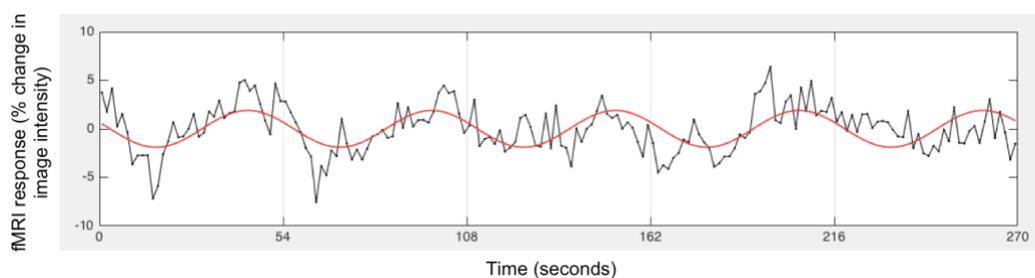


Figure 3. Example of average time series for single voxel. Voxel [19 48 15] from RH of participant 2.

The phase values that mrTools computes are of particular importance because they provide insight into the spatial 'preference' of the individual voxel. Depending on the area of space coded for by a voxel, activity will increase as saccades are made to targets progressively closer to this represented area and decrease as saccades are made to targets more and more distant from the represented area, hence why you would expect to see an oscillating wave.

It is possible to work out which saccade target is eliciting the greatest activation by looking at the x-axis time values under the peaks of the time series curve and comparing these times to the timing of stimulus presentation. The phase values that mrTools computes equate to the difference in phase between the time series wave and a standard sinusoid curve. A standard sinusoid curve has an origin at zero, a positive peak at 90° , crosses the x-axis at 180° , has a trough at 270° , and returns to the x-axis at 360° . The saccade target at 3 o'clock would therefore have a phase value of zero, since activation would peak at 13.5 seconds (or 90°), the same as a sine curve. If we consider successive targets clockwise from the 3 o'clock target, presented at 4.5-second intervals and 30° apart, with each successive target the peak of the sinusoid curve would move 4.5 seconds to the right along the x-axis. The curve would be described as having undergone a 30° phase shift.

The next stage was to define the ROI using anatomical boundaries. As discussed, the ROI for this study was the IPS and the various functionally distinct subregions it includes: VIP, MIP, LIP, AIP (anterior intraparietal) and CIP (caudal intraparietal). In the majority of participants, the IPS begins at or around the middle of the postcentral sulcus and travels in a posterior fashion toward the occipital lobe until it joins with the transverse occipital sulcus. When drawing our ROIs, we identified the IPS on the lateral surface of parietal cortex and wrapped around it, including the gyri either side. ROIs were drawn on inflated cortical surfaces and these inflated surfaces were generated via the open software suite FreeSurfer (<https://surfer.nmr.mgh.harvard.edu/>). The surface selected for use included only grey matter voxels. The ROI was extended through the entire cortical depth using the depth conversion tool and restricted to voxels with a coherence value greater than 0.3. Re-drawing the ROI for each condition would have meant comparing different voxels when comparing conditions, not only because drawing the ROI by hand would inevitably mean the boundary would be slightly different each time, but also because those voxels meeting the coherence minimum would be different. To ensure a fair comparison, the ROI was defined in the 'far' condition and then copied and pasted into the 'near', 'left' and 'right' conditions. The final step was to extract the coherence and phase values for all voxels included in the restricted ROI.

Results

Colour Maps

A coherence threshold was applied to the data such that only voxels with coherence greater than 0.3 were included in the analysis ($p < .05$). The appropriate level for the coherence threshold was decided using the interrogate overlay function. The mrTools interrogate overlay function calculates the contrast-to-noise ratio (CNR) for the voxel and displays it alongside a Fourier spectrum. Time series in fMRI are the combination of an activation signal time course and a noise signal time course. The activation signal time course is the baseline signal plus fluctuations resulting from the experimental task, i.e. the hemodynamic response function (HRF). The noise signal time course is a result of system noise, physiological noise, task-related noise and other such noise sources (Welvaert & Rosseel, 2013). The SNR can be calculated by taking the mean of the activation signal time course and dividing it by the standard deviation of the noise signal time course. The CNR can be calculated in a number of different ways. In this instance, it has been calculated by taking the magnitude at a frequency of five (the stimulus periodicity) and dividing it by the mean magnitude of all other frequencies in the time series. In the absence of noise, we would expect the time series curve to have a frequency of five because the subject completed five cycles around the clock and so activation would rise and fall systematically five times, regardless of which saccade target was eliciting the greatest activation. In every condition and in the case of both subjects, there were examples of high coherence voxels that produced interrogation results similar to those shown in **Figure 4A**, with a high CNR. Although this shows that the basic paradigm was successful, we went on to interrogate voxels across the full range of coherence values. **Figure 4** presents the interrogation output for example voxels with decreasing levels of coherence A-E. The Fourier spectra for A and B look very clear, C and D are less clear, and in E, the magnitude at the stimulus periodicity is matched and even superseded by the magnitude of various other frequencies, therefore suggesting that a coherence threshold of 0.3 was most appropriate for the present data.

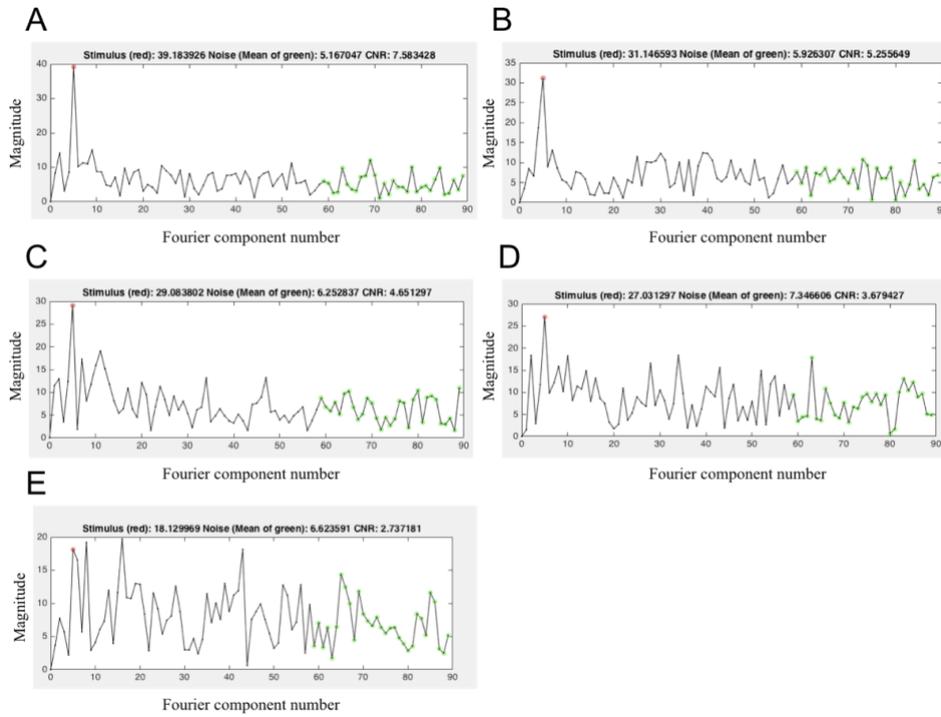


Figure 4. The Fourier spectrum and CNR value at various levels of coherence. (A) $co = 0.52$ (B) $co = 0.35$ (C) $co = 0.30$ (D) $co = 0.35$ (E) $co = 0.22$.

Figure 5 presents those voxels that surpassed the 0.3 coherence threshold. Each voxel is coloured according to its coherence level, with blue indicating voxels just above the threshold and green and yellow indicating voxels with greater coherence. In **Figure 6**, each voxel is coloured according to its phase value, with red indicating a phase shift of zero, green a phase shift of 90° (or 1.57 radians), blue a phase shift of 180° and purple a phase shift of 270° . **Figures 5** and **6** presents data for the entire scan area, however, for the analysis, only voxels within the ROI were considered. The ROI for this study can be seen in **Figure 7**, with the bottom images showing the ROI following restriction (the removal of any voxels with a coherence below 0.3). As can be seen, the number of voxels within the ROI boundary that surpassed the coherence threshold was low; 83 for the left hemisphere and 70 for the right hemisphere of subject one, and 76 for the left hemisphere and 88 for the right hemisphere of subject two. However, there was still comfortably more values than the minimum number of ten cases per condition required to run the comparison tests.

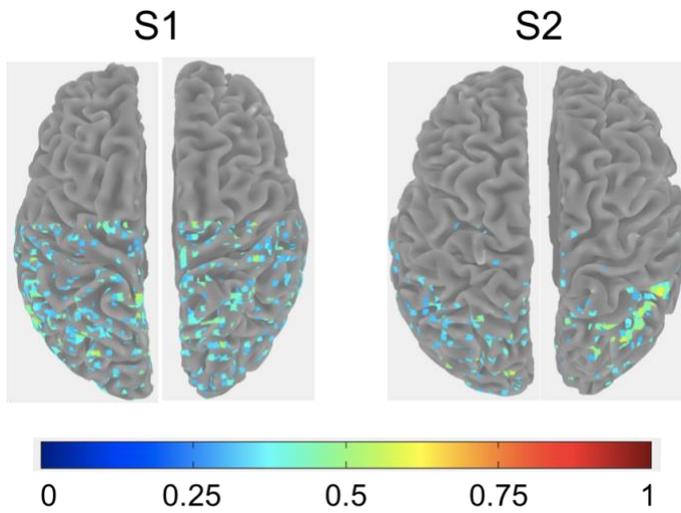


Figure 5. Grey matter voxels colour coded according to coherence value (only voxels with coherence > 0.3 included).

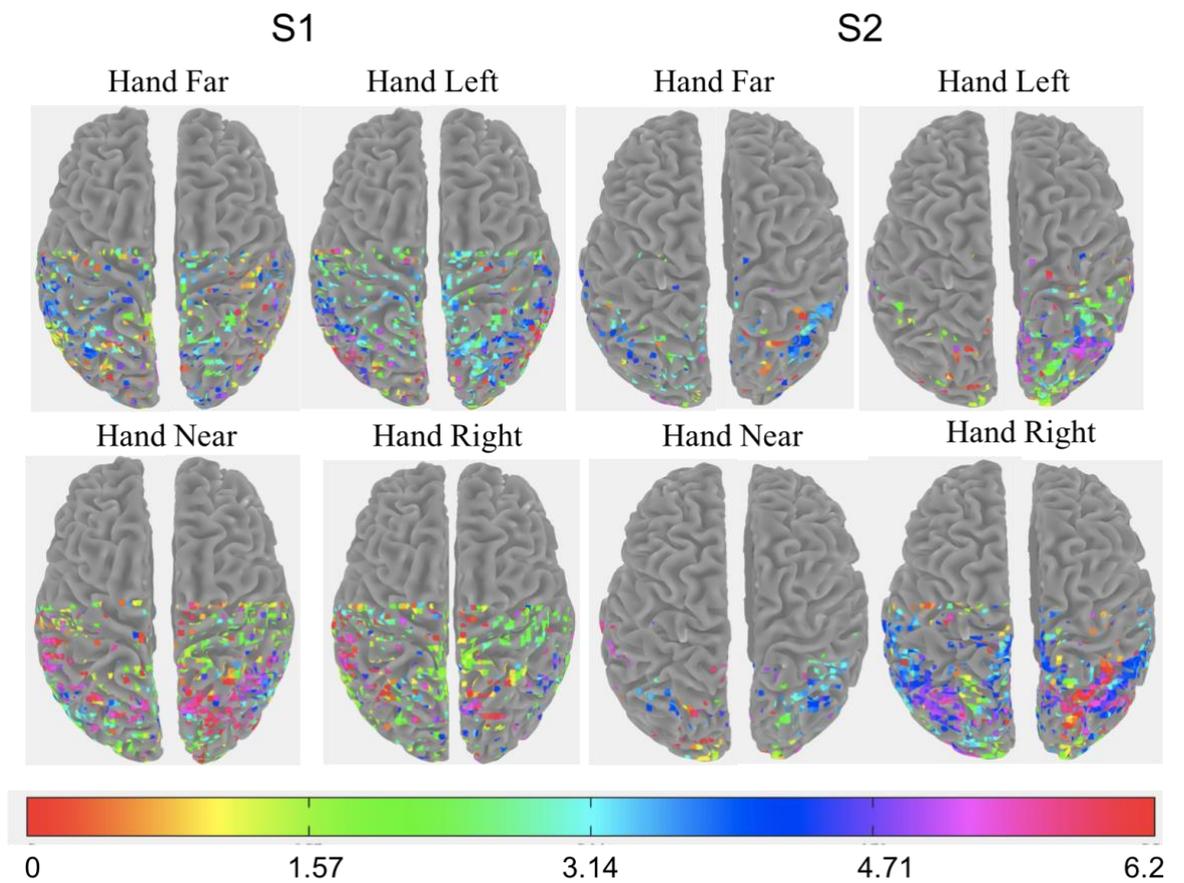


Figure 6. Grey matter voxels colour coded according to phase value (only voxels with coherence > 0.3 included).

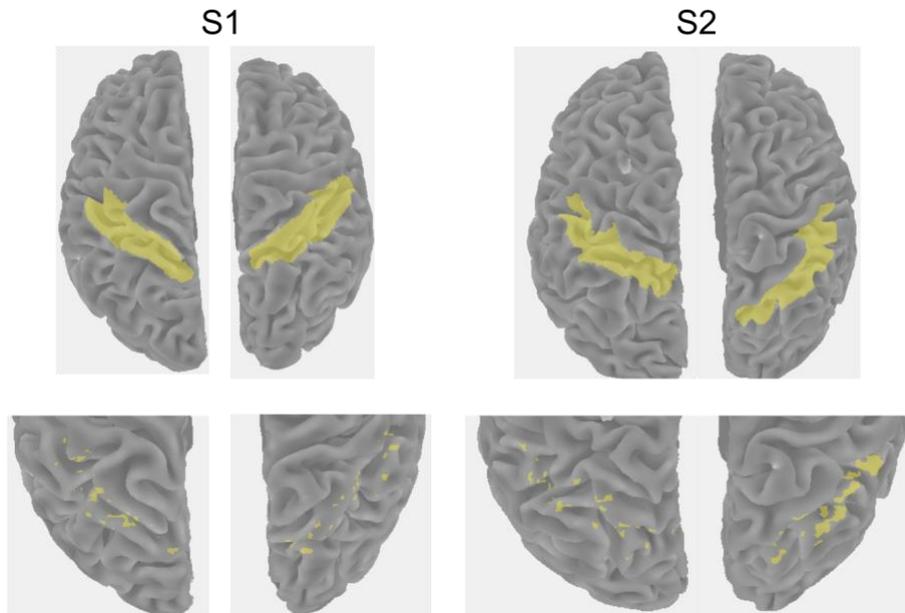


Figure 7. Left and right hemisphere restricted and non-restricted ROIs on the inflated cortical surfaces. ROI restriction was conducted on the ‘far’ condition data.

Rose Plots

Another way to display the phase information is with a rose histogram (**Figure 8**), the circular equivalent of a column chart. Just like a column chart, the columns represent frequency, which in this case is the number of voxels with a phase value that falls within the 20° ‘bin’ covered by the column. It is important to keep in mind that the colour scale in **Figure 6** is used to represent the phase value of the voxel and *not* the angle of the target producing the greatest increase in image intensity. As discussed, the angle of the target producing the greatest increase in image intensity is related to the x-axis time values under the peaks of the time series curve. For example, if the curve were to peak at 4.5 seconds and every 54 seconds thereafter for five cycles, the angle of the target producing the greatest response would be 30° (i.e. the 1 o’clock target). The phase value on the other hand is the degree of horizontal shift a standard sinusoid curve would have to undergo in order to become the waveform created by the time series. Since the positive peak of the reference sinusoid wave is at 90° , the angle of the target producing the greatest increase in image intensity is the phase value plus 90° . Therefore, to aid interpretation, the rose plots have been rotated 90° clockwise allowing for phase and target angle to be interpreted simultaneously, with the former being taken from the axis label and the latter being the literal direction that the bar is pointing. Separate rose histograms were created for each hemisphere.

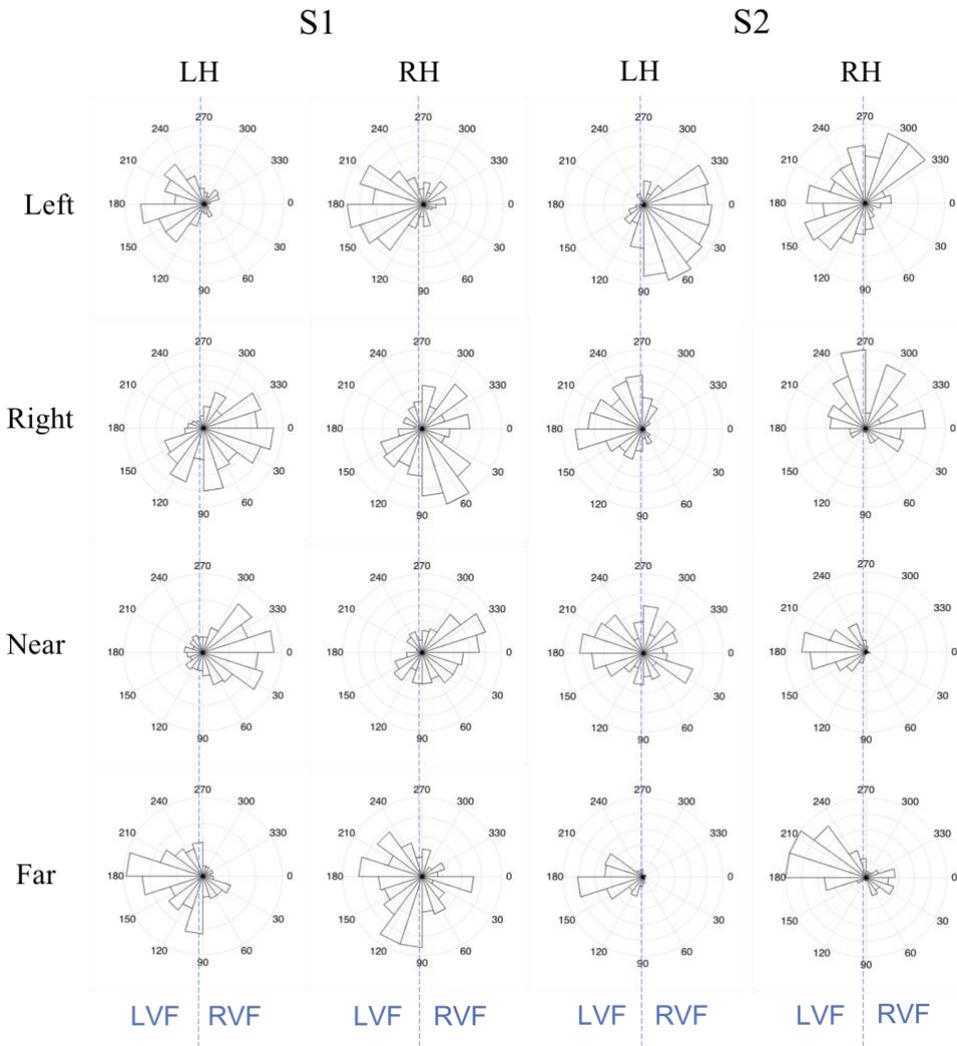


Figure 8. Rose histograms for left and right hemisphere, for all four conditions.

LH = Left Hemisphere, RH = Right Hemisphere, LVF = Left Visual Field, RVF = Right Visual Field.

Statistics

All statistics were performed using the CircStat Matlab toolbox (Berens, 2009). Within Matlab, each subject folder contained eight matrices of phase values (in radians), one for each hemisphere for each of the four conditions. The number of values within a matrix corresponded to the number of voxels within the defined ROI with a coherence value greater than 0.3, for that particular subject and hemisphere. **Table 1** shows the median phase value in radians (but presented as 0 to π and 0 to $-\pi$, as opposed to 0- 2π) and standard deviation for each subject, condition and hemisphere. The median and not the mean is reported because the circular data equivalent of a t-test or one-way ANOVA is the Watson-Williams test for equal means, and, similar to how the linear tests assume a normal distribution, one assumption of this test is that the data follows a von Mises

distribution. Our data failed to meet this assumption and so the appropriate test was the non-parametric multi-sample test for equal medians (circ_cmtest within the CircStat toolbox), suggested by Fisher (1995) and similar to the Kruskal-Wallis test for linear data.

Table 1

Median and Standard Deviation Values Following Coherence Threshold Increase

Subject	Condition	LH		RH	
		Med	Std	Med	Std
S1	Hand Left	3.13	1.04	2.87	1.07
	Hand Right	0.77	1.10	0.93	1.14
	Hand Near	0.19	1.08	0.50	1.19
	Hand Far	2.97	1.13	2.19	1.16
S2	Hand Left	0.64	0.80	2.90	1.22
	Hand Right	-2.87	0.98	-1.94	0.99
	Hand Near	-1.32	1.37	-2.94	0.69
	Hand Far	2.98	0.75	-2.75	0.87

Notes. Med = median. Positive median direction values ($0-\pi$) represent 0° clockwise through to 180° and negative median direction values ($0-\pi$) represent 360° anticlockwise through to 180° .

Figure 9 presents these median values (in a $0-360^\circ$ format) on rose plots. This second set of rose histograms are not technically histograms as they do not provide any information regarding frequency; the plots are based on a single value (the median). They do however make it easier to compare between conditions. Crucially, we can observe whether the saccadotopic maps have reorganised following a change in hand position by looking to see whether the median points in different directions for different conditions. If the neurons in this region are using hand-centred coding, the phase values will change when hand position changes because the receptive fields of the underlying neurons will shift with the hand, leading to a new region of space being spatially represented and therefore a different target eliciting the greatest response. Calculating the median of all the phase values within the ROI and comparing these medians using the multi-sample test for equal medians provides an objective and statistical method of assessing whether the topographic mapping within the ROI has reorganised and the significance of this reorganisation.

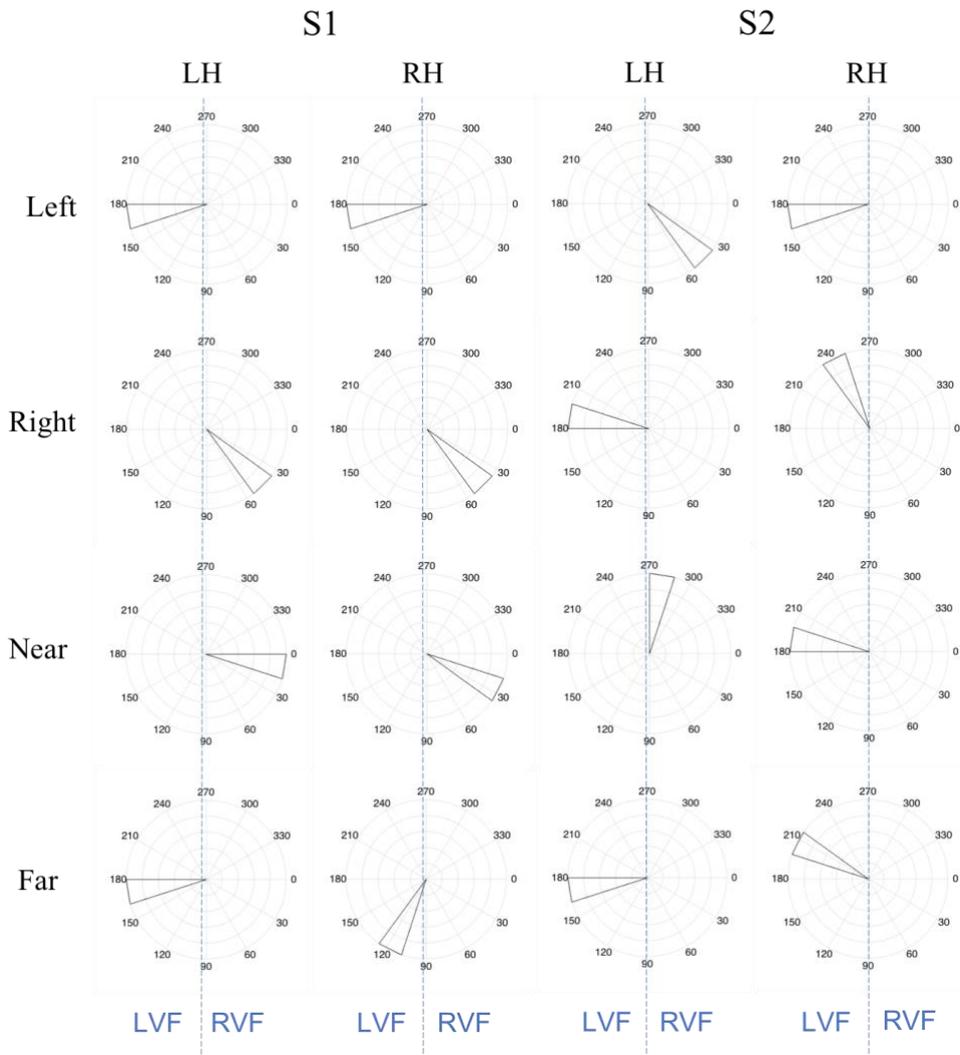


Figure 9. Median direction for left and right hemisphere, for all four conditions.

LH = Left Hemisphere, RH = Right Hemisphere, LVF = Left Visual Field, RVF = Right Visual Field.

Table 2 shows the results of the between-condition comparison tests (left with right and near with far) and **Table 3** shows the results of the within-condition comparison tests (left hemisphere with right hemisphere). For subject one, the difference in average phase between hand left and hand right, and between hand near and hand far, was highly significant in both hemispheres. For subject two, the difference in average phase between hand near and hand far was significant in both hemispheres, albeit more modestly, and the difference between hand left and hand right was significant in left hemisphere but non-significant in right hemisphere. Comparing the two hemispheres, for subject one the difference was non-significant within every condition, with the two hemispheres always coding for the same or very similar region of space. Conversely, for subject two the

difference between left and right hemisphere was significant within every condition except hand near.

Table 2

Results from the Between-Condition Multi-Sample Tests for Equal Medians

Subject	Comparison	LH		RH	
		<i>P</i>	<i>pval</i>	<i>P</i>	<i>pval</i>
1	Left vs Right	44.55	<.001	19.31	<.001
	Near vs Far	34.80	<.001	13.83	<.001
2	Left vs Right	9.50	<.01	0.36	.55
	Near vs Far	3.79	.05	4.45	.03

Notes. *P* = test statistic, *pval* = significance value.

Table 3

Results from Within-Condition Multi-Sample Tests for Equal Medians

Condition	S1		S2	
	<i>P</i>	<i>pval</i>	<i>P</i>	<i>pval</i>
Hand Left	1.50	.22	9.81	<.01
Hand Right	0.06	.80	7.95	<.01
Hand Near	0.33	.57	0.88	0.35
Hand Far	1.88	.17	25.11	<.001

Notes. All comparisons are between left and right hemisphere.

Discussion

It has been well documented that the topographic maps of the IPS respond predominantly to stimuli within the contralateral field (Konen & Kastner, 2008; Schluppeck, Curtis, Glimcher, & Heeger, 2006; Schluppeck et al., 2005; Silver & Kastner, 2009; Silver, Ress, & Heeger, 2005; Swisher, Halko, Merabet, McMains, & Somers, 2007). A model map would represent 0-180° and 180-360° in the left and right hemispheres respectively, with an equal number of voxels coding for the space either side of 90/270° and a slight horizontal bias, leaving the vertical meridian underrepresented (Silver et al., 2005). If we were to calculate the average phase values for these model maps and display them on our rotated rose histograms, the left hemisphere plot would point 90° and the right hemisphere plot would point 270°. Of course, in reality, topographic organisation is not quite so uniform and maps vary both within and across individuals. Although this means we might not see an exact ‘dead right’ and ‘dead left’ preference, a contralateral bias should still emerge. Including a control condition whereby subjects perform the task with their hand in a neutral position (resting on the scanner bed and adjacent to the body) would have allowed us to test for contralateral bias and use it as a further indication that the basic paradigm had been successful. Not doing so is unarguably a shortfall of the study, however, *two* previous studies using the exact same stimuli, scanning parameters and analysis procedure have inadvertently tested this hand position during their centre gaze (Connolly et al., 2015) and centre torso (Connolly et al., in preparation) conditions, and reported a visible contralateral bias in the resulting phase maps.

In the present study, the median phase values for participant one at hand left were 179° and 164° for left and right hemisphere respectively, equating to a spatial preference very near to the saccade target at 270°, *on average* across left-lateralised runs. This spatial preference is exactly what we would expect from right hemisphere in the absence of the hand manipulation, but the opposite of what we would expect from left hemisphere; placing the right hand to the left of the body midline would appear to have caused a complete 180° inversion of spatial representation within left hemisphere. At hand right, the results are very nearly a mirror image. The median phase values for hand right were 44.1° and 53.3° for left and right hemisphere respectively, equating to a spatial preference either side of the 5 o’clock target at 140°. Therefore, placing the right hand further to the right than it would be ordinarily would appear to have caused a similar inversion of spatial representation within right hemisphere. For both conditions, the difference in average phase between left

and right hemisphere was non-significant; the two were representing the same or nearly the same region of space. Crucially, the difference in average phase between hand left and hand right was highly significant. With both hemispheres optimally responding to targets on the same side as the hand, it could be argued that the high-coherence spatially tuned neurons within our ROI are using a hand-centred coordinate frame; their receptive fields are anchored to the hand and therefore occupy the left visual field during the hand left condition and right visual field during the hand right condition.

Similar phase inversions have been reported as a result of torso (Connolly et al., in preparation) and gaze angle (Connolly et al., 2015) manipulations. This evidence for head and body-centred coding does not conflict with the present evidence for a hand-centred coordinate scheme, as it is possible that all three coordinate schemes exist as distinct subsets of neurons within IPS, or that the same neurons are able to switch flexibly between coordinate frames. Visual receptive fields anchored to the hand or arm have been reported in non-human primate premotor cortex (Graziano, 1999). In this study, monkeys viewed a 5cm-diameter ball moving along different trajectories toward the body. Single-cell recordings were taken in response to all four trajectories, with the hand and forearm directly below the third trajectory in one condition, and directly below the second trajectory in another. For some bimodal neurons, the visual and tactile receptive fields remained aligned i.e. when the arm moved, the visual receptive fields moved with it. More recently, in an fMRI experiment, Makin, Holmes, and Zohary (2007) reported clusters of voxels in IPS that showed decreasing activation as the participant's left hand was retracted from a stationary ball. Moving the hand and not the visual stimulus ensured a constant retinal projection, therefore the preference for the near over the far ball could be attributed to hand-centred neurons and not low-level visual differences. A cortical representation of hand position is necessary for a receptive field to remain in spatial register with the hand. Evidence from behavioural studies has taught us that the representation of hand position depends upon input from the skin, joints, muscles, eyes and ears (Edin & Johansson, 1995; Lackner & DiZio, 2000; Smeets, van den Dobbelen, de Grave, van Beers, & Brenner, 2006). Although the integration of this sensory information provides a better estimate of hand position than any one source of information alone (Snijders, Holmes, & Spence, 2007; van Beers, Sittig, & Gon, 1999), both the Graziano (1999) and Makin et al. (2007) studies demonstrated that a single source of information is sufficient; the visual receptive fields remained anchored to the movement of a dummy arm (visual input only) and to their own occluded arm (proprioceptive input only). The present study was conducted in the

dark and so it too demonstrates that proprioceptive input from the elbow joint, shoulder joint, and arm muscles is enough to guide hand-centred representations.

The results for participant one at hand near and hand far were very similar to the results at hand right and hand left. For hand near, the median phase value for left hemisphere was 10.9° and the median phase value for right hemisphere was 28.6° , therefore, on average across near left and near right runs, activity was greatest in response to the 3 o'clock and 4 o'clock targets. For hand far, the median phase value for left hemisphere was 170° and the median phase value for right hemisphere was 125° , indicating a spatial preference for the 9 o'clock and 7 o'clock targets respectively. As before, the difference between hemispheres was non-significant for both conditions and the difference between conditions was highly significant for both hemispheres. Again, compared to the expected contralateral bias results of a hand neutral condition, the spatial representation of one hemisphere has completely or partially inverted to the opposite hemifield. A highly significant difference in average phase between hand near and hand far is quite a striking result considering that the restrictions of the bore only allowed for a 13cm difference in depth. On the other hand, it is not obvious why placing the hand near to the body would lead to greater activation for right visual field targets or why placing the hand further from the body would lead to greater activation for left visual field targets.

Significant differences between conditions were also found for participant two, but, the results are not consistent across participants. The hand far condition is the only condition to produce comparable results, with both hemispheres demonstrating a spatial preference near to the 270° target. For hand left and hand near, the phase maps of participant two present contralateral bias, and at hand right, we get the exact opposite of the spatial preference reported for participant one. With so many inconsistencies, it is difficult to put together a strong argument for hand-centred representation within human PPC based on the results of this two-participant experiment. It is our opinion that we have a working paradigm, but that alternative methods of analysis should be investigated before investing in a larger scale study. All options connected to the current analysis procedure (coherence threshold level, degree of shift, size of ROI etc.) have been exhausted. The issue is thought to lie with the ROI method, selecting and entering voxels into the analysis based on imprecise, anatomically-guided manual selections on the lateral surface of very individual brains. In the 'future research' section we discuss alternative methods of voxel selection that could help restrict the analysis to populations of same-coordinate-frame neurons.

3. Experiment 2 - Eye Tracking

Method

Subjects

Ten postgraduate students (three male) were recruited from the Department of Psychology at Durham University. All subjects were right-handed, over eighteen years of age ($M = 28$ years), and had no history of neurological defects. Of the ten subjects, seven had normal vision and three had corrected vision. Those with corrected vision wore their glasses during testing. Individuals requiring contact lenses were not recruited. The Durham University Department of Psychology Ethics Committee approved both the behavioural and the neuroimaging experiment included in this study.

Conditions

Subjects sat in a purpose-built chair attached to a circular rotatable platform; essentially two wooden disks separated by a series of small wheels along the perimeter. A red arrow on the top disk marked the midline of the chair and black arrows on the bottom disk marked 0° , 90° leftward and 90° rightward of the screen midline. The chair was rotated until the red arrow pointed to one of the black markers below, producing three consistent torso positions. When subjects were rotated 90° left or right in the chair, they had to twist their torso so that their knees were pointing in the direction the chair was facing but their head was still forward facing, with their chin in the chin rest.

As well as manipulating torso position, we simultaneously manipulated hand position. In every trial, subjects had their left hand placed on the knee and their right hand flat on the desk in front of them, either to the left or to the right of the screen midline. We asked participants to reach as far left and as far right as they could whilst still remaining comfortable. We did not have fixed hand positions across participants, since subjects were all different heights and with different arm lengths. Rather, we increased within-subject consistency by marking off the initial left and right-hand placement with tape, so that the same position could be assumed for the remaining two torso positions. To increase between-subject consistency, we asked all subjects to ensure their elbow was fully extended and that their little finger was in line with the edge of the desk when their hand was to the right, and that their thumb was in line with the desk when their hand was to the

left. Bodily restrictions meant the leftward position was much closer to the midline (28cm, on average) than the rightward position (65cm, on average).

The three torso positions and two hand positions meant there were six conditions in total: hand left and hand right, at torso left, torso centre and torso right (see **Figure 10**). The order of conditions was determined by numbering the conditions and then using a pseudo-random number generator to generate eleven sets of six unique numbers ranging from one to six (**Appendix G**). It was important to pseudo-randomise the order of conditions, not only to allow for fatigue, but to allow for the decline in concentration and interest toward the end of the experiment that inevitably occurs when performing a mundane and repetitive task.

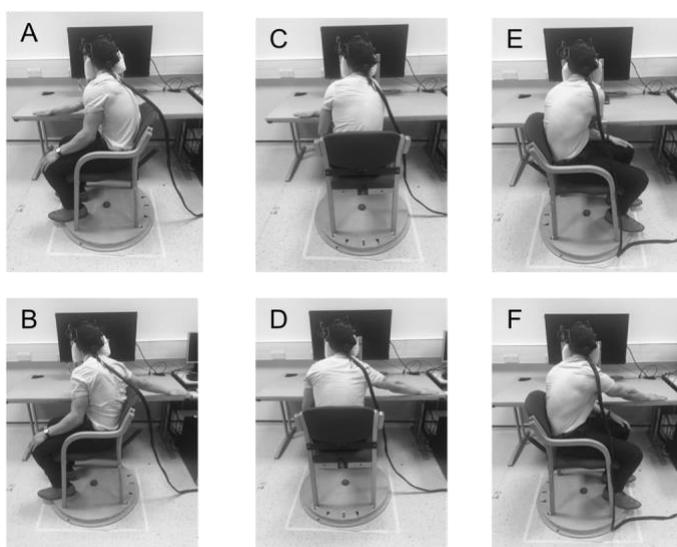


Figure 10. Images A-F illustrate the six experimental conditions. (A) Torso left, hand left. (B) Torso left, hand right. (C) Torso centre, hand left. (D) Torso centre, hand right. (E) Torso right, hand left. (F) Torso right, hand right.

Procedure

Subjects were recruited using opportunity sampling. When subjects arrived at the lab, they were seated and given time to read through the information sheet (**Appendix H**) before completing a consent form (**Appendix C**). The experimenter started by explaining the saccadotopy task. After explaining the task, the experimenter mounted the eye tracker to the subject's head, tightening at the top and back of the head until the device was secure yet comfortable. The infrared eye tracker used in this experiment was the Eyelink 1000 (SR Research, Ottawa, Canada) (**Figure 11A**), with a sampling rate of 2,000 Hz, 0.25°-0.5° average accuracy, and 0.01° RMS resolution. Since the experiment only required

monocular eye tracking, the left camera was moved and fixed in a position out to the side, so as not to occlude any part of the visual field. The right camera was manipulated until the right eye filled the screen display and the pupil was roughly central. The pupil threshold was initially set using auto threshold, and then manually adjusted as the subject looked to the four extreme corners of the screen. The optimal position for the camera, whereby the pupil was reliably picked up but the camera did not occlude any of the targets on the screen, tended to be just below the eye, roughly in line with the tip of the nose. For this study we used pupil tracking, not corneal reflection, with the sampling rate set to 250 Hz. Stimuli were presented on a 708mm x 398mm screen (2560 x 1440 pixels), with a maximum refresh rate of 60 Hz. This screen was positioned 52cm forward from the chin rest.

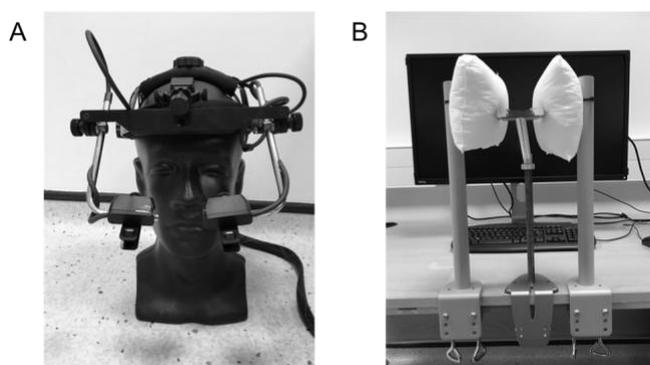


Figure 11. (A) Eyelink 1000 infrared eye tracker by SR Research. (B) Chin rest and custom-built head stabiliser.

Subjects completed six runs of the saccadotopy task in total, one for each of the six conditions. Each run lasted approximately 4.5 minutes. Before these six runs, subjects completed a practice run to familiarise themselves with the task. A single run involved five cycles ‘around the clock’, that is, within one run, subjects made five saccades to each of the twelve target locations. Prior to a run, subjects were instructed which position to assume and were assisted in assuming this position correctly. Cushion pads attached to desk clamp poles either side of the chin rest (**Figure 11B**) were positioned such that they pressed up against the subject’s cheeks. This purpose-built head restraint was designed to minimise head movement during runs. Subjects were released from the head restraint between runs to allow them to stretch and rest before assuming the next static position. For this reason, we ran the eye tracker calibration and validation procedure before the start of each run. The total time required for setting up the eye tracker, training, actual testing and appropriate rest intervals equated to anywhere between 60 and 90 minutes in the lab. Half way through testing, the eye tracker was removed from the subject’s head for a short

period, since the device is heavy and can become uncomfortable if worn for extended periods.

Data Analysis

The raw data files were imported from Matlab into Eyelink Data Viewer 2.6 (SR Research, Ottawa, Canada). Data Viewer allows for the cycles within a run to be viewed separately, displaying the end points of every saccade made within that single cycle. The first step was a process of eyeballing the data from each cycle, across all conditions and participants. There were no strict criteria at this stage; the experimenter was looking for a cluster of data points in the centre around fixation, and a ring of data points around this cluster, as an indication that the saccadotopy task had been understood and performed correctly. The five variables chosen for extraction within the saccade report were as follows: 'saccade amplitude', measured in degrees of visual angle (DVA), 'saccade start time', measured in milliseconds relative to the beginning of a cycle, 'saccade end x' and 'saccade end y', providing the x and y coordinates of saccade endpoints in pixels, and 'trial label', numbered from one to five to distinguish cycles. A saccade report was executed for each run and the output saved in a subject-specific and condition-specific named excel file.

The eye tracking analysis was then performed via four custom Matlab scripts. The first script organised the data, assigning the appropriate kinematic labels and dividing the data up into a three-tier directory structure of subject files, condition files and cycle files. The second script distinguished intentional saccades, executed appropriately in response to the task, from wrongly executed saccades and involuntary eye movement. This was achieved in two ways. First, an amplitude threshold was applied, so that only saccades with amplitude greater than or equal to eight DVA were considered. This effectively discarded the many saccades recorded as a consequence of retinal jitter, which inevitably occurred as the subject held gaze on the fixation cross. Second, a series of temporal thresholds were applied, creating ten 1,000 ms time windows. Saccades initiated outside of these time windows were discarded. The lower boundaries of these time windows corresponded to the time points at which the subject was cued to execute a saccade by the disappearance of the distracter annulus. There were ten time windows and not twelve because saccades directed towards the 12 o'clock and 6 o'clock targets were not of interest, since they do not uniquely belong to the left or right visual field. If more than one saccade fell within a single time window, the saccade initiated first was held onto and the others discarded. Note that not every saccadotopy run produced data for all ten targets of interest; for some

targets, there were no saccades that met both the minimum amplitude and temporal criteria. At the end of the script, all of the variables belonging to saccades executed within the first five time windows, i.e. with a start time of anywhere up to 27,750 ms, were renamed as right visual field kinematics, whilst all of the variables belonging to saccades executed after 27,750 ms were renamed as left visual field kinematics.

The third of the four scripts calculated four measures of performance for each target that produced a valid saccade. Amplitude error was calculated by using the x and y coordinates of the saccade endpoint to calculate the distance (in pixels) from the fixation cross, before subtracting the distance of the target from the fixation cross (260 pixels). Therefore, positive values indicated that a saccade was hypermetric, whilst negative values indicated that a saccade was hypometric. Similarly, angular error was calculated by using the x and y coordinates of the saccade endpoint to calculate the angle (in radians) from the 12 o'clock position, before subtracting the angle of the target from the 12 o'clock position. Therefore, positive values indicated an endpoint was further clockwise in relation to the target, whilst negative values indicated an endpoint was counter clockwise in relation to the target. Amplitude and angular error were then combined, to provide an understanding of the spatial relationship between the saccade endpoint and the target in terms of a Cartesian coordinate plane (positive values only). Reaction time was calculated by subtracting saccade start time from the time point at which the subject was cued to execute the saccade.

Finally, the fourth script calculated a series of averages. The first level of averaging involved averaging across each hemi field. This created eight values per cycle: a left visual field mean and a right visual field mean for each of the four different measures. The second level of averaging involved averaging the five cycles within a run. The third level of averaging involved averaging across the ten subjects, within each condition.

Results

Although the custom Matlab code calculated the across subject means, the data was entered into SPSS before this final level of averaging. This data had been averaged across targets within the same visual field and across the five cycles within a run. Therefore, each of ten subjects was left with one right and one left visual field value for all four kinematics, for each of the six conditions. A post hoc G-Power analysis confirmed that having ten subjects was sufficient to demonstrate a medium effect size ($d = 0.5$).

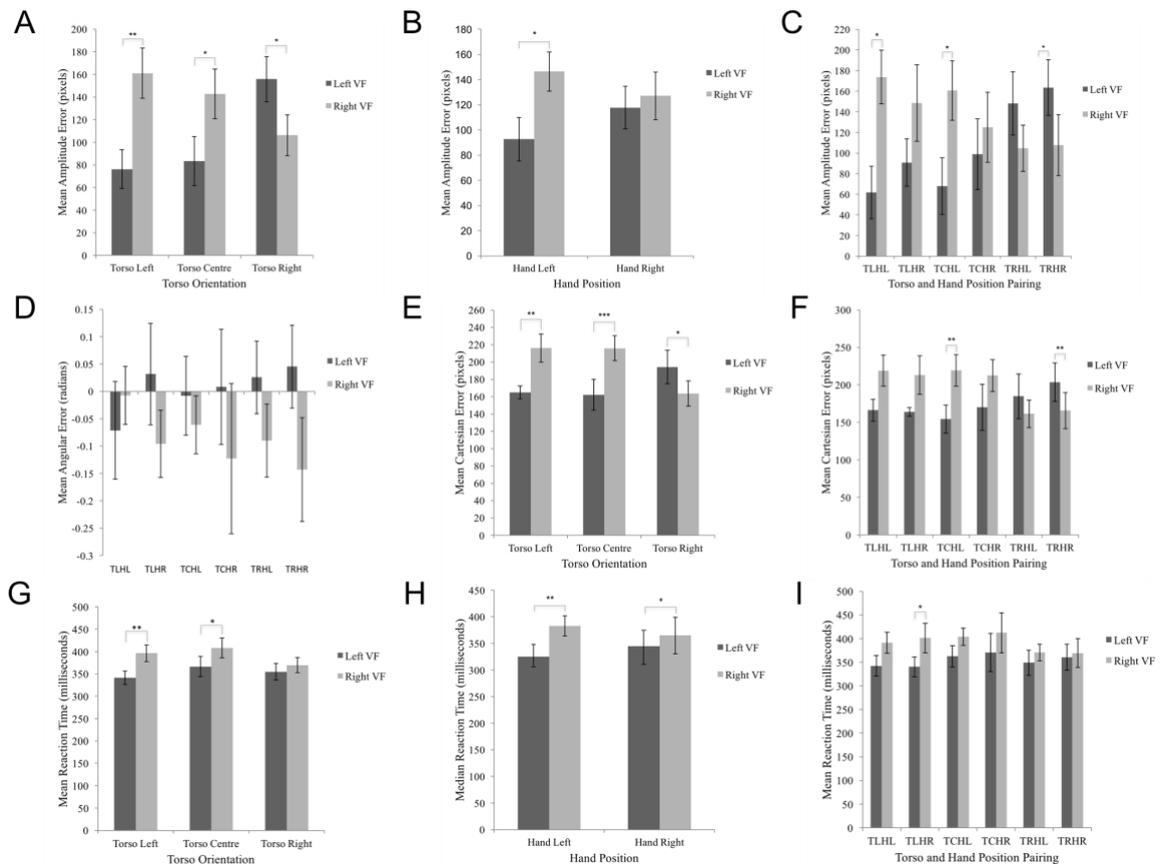


Figure 12. The effect of torso orientation on the difference in mean (A) amplitude error, (E) Cartesian error, and (G) reaction time, between left and right visual field saccades. The effect of hand position on the difference in mean (B) amplitude error, and (H) reaction time, between left and right visual field saccades. Mean (C) amplitude error, (D) angular error, (F) Cartesian error, and (I) reaction time, for left and right visual field targets, for all six conditions.

Amplitude Error

Since each subject participated in all six conditions, the appropriate means comparison test was a Repeated Measures ANOVA. **Table 5** presents the left and right visual field means

and standard deviations for the six torso and hand position combinations. Torso rotation and hand placement were entered into the ANOVA separately, as three- and two-level within-subject factors respectively, along with the two-level within-subject factor ‘visual field’. This made the test a two-way repeated measures ANOVA. The Sidak correction was selected for application across all tests.

Table 5

Mean Amplitude Error (pixels) for Left and Right Visual Field Targets by Condition

Condition	Left VF		Right VF	
	Means	SD	Means	SD
TLHL	61.7	80.6	174	82.1
TLHR	90.8	72.4	148	117
TCHL	67.9	86.9	161	91.5
TCHR	98.8	108	125	108
TRHL	148	96.7	105	71.1
TRHR	164	85.5	108	93.3

Notes. Within the condition abbreviations, ‘T’ = torso, ‘H’ = hand, ‘L’ = left, ‘C’ = centre, ‘R’ = right. In addition, VF = visual field, SD = standard deviation.

Mauchly’s test of sphericity indicated that the assumption of sphericity had been met for the effect of torso, $\chi^2(2) = 1.67, p = .43$, and any interaction effect including torso ($p > .05$ for all). Results were not provided for the effect of hand, visual field, or the interaction between the two, since sphericity is only an issue for factors with three or more levels. The main ANOVA table revealed that the effect of visual field was non-significant, $F(1,9) = 1.81, p = .21$. This means that if we were to disregard the manipulations made, amplitude error was not significantly greater or smaller for saccades made to targets within the left, as opposed to right, visual field. The main effect of torso, $F(2,18) = 1.09, p = .36$, and the main effect of hand, $F(1,9) = .07, p = .80$, were also non-significant. This means that if we were to disregard visual field, that is, if we were to consider all twelve targets, amplitude error was not significantly greater or smaller for left hand position runs as opposed to right hand position runs, or between left, centre and right torso orientations. The main ANOVA table did however reveal a very highly significant interaction between torso and visual field, $F(2,18) = 12.06, p < .001, \eta_p^2 = .57$, with a large effect size. This means that the *difference* in amplitude error between left and right saccades changed significantly depending on the orientation of the torso. The difference in amplitude error between left and right also changed depending on the placement of the hand, however this interaction

effect was marginally non-significant, $F(1,9) = 3.62$, $p = .09$, $\eta_p^2 = .29$. The smaller but still large effect size would suggest that this effect might have reached significance had the sample size been larger.

Figure 12A provides an illustration for the interaction effect of torso and visual field on saccade amplitude error. As mentioned, values for amplitude error could be positive (hypermetric) or negative (hypometric). Note that all mean values are positive. Looking first at the torso centre control condition, it can be observed that saccades towards right visual field targets are more hypermetric (or less accurate) than saccades towards left visual field targets. A paired samples t -test revealed that, for the torso centre condition, the mean right visual field amplitude error was significantly greater ($M = 143$ pixels) than the mean left visual field amplitude error ($M = 83.4$ pixels), $t(19) = -2.08$, $p = .05$. When the torso was rotated leftward, the mean amplitude error for left visual field targets reduced ($M = 76.3$ pixels) whilst the mean amplitude error for right visual field targets increased ($M = 161$ pixels), causing the difference between the two to increase in significance, $t(19) = -3.03$, $p < .01$. In contrast, when the torso was rotated to the right, the mean amplitude error for left visual field targets increased in comparison to the control condition ($M = 156$ pixels), whilst right target mean amplitude error reduced ($M = 106$ pixels). These changes resulting from a rightward rotation were large enough for the right and left visual field means to not only move towards each other but to surpass each other, so that the relationship between the two reversed, with the mean amplitude error of right targets becoming significantly smaller than the mean amplitude error of left targets, $t(19) = 2.43$, $p = .03$.

Figure 12B illustrates the interaction effect of hand position and visual field. When the hand was placed to the left of the body midline, the mean amplitude error of saccades made towards left visual field targets ($M = 92.6$ pixels) was significantly smaller than the mean amplitude error of saccades made towards right visual field targets ($M = 146$ pixels), $t(29) = -2.2$, $p = .04$. When the hand was placed to the right, the mean amplitude error for left targets ($M = 118$ pixels) remained smaller than the mean amplitude error for right targets ($M = 127$ pixels), but the difference between the two reduced dramatically and became non-significant, $t(29) = -.42$, $p = .68$. Since there was no hand centre condition, the *change* to the amplitude error as a result of the hand manipulations cannot be quantified. If we were to assume that the hand centre condition would look somewhat similar to the torso centre condition, with greater amplitude error for right visual field, it is reasonable to suggest that the hand manipulation has altered the left and the right visual fields in the

same manner. The hand position effect being weaker, as suggested by the marginally non-significant p value, could explain why the relationship between the left and right visual field switches for torso right but not for hand right; the hand right manipulation has caused the means to move towards each other but not enough to surpass each other.

The standardised residuals from the repeated measures ANOVA were saved and tested for normality using the Shapiro-Wilk test. A non-significant result ($p > .05$) for all six groups meant we could accept the null hypothesis that the distribution of amplitude error values was not significantly different from a normal population. Figure 12C illustrates amplitude error for left and right visual field saccades, for all six experimental conditions.

Angular Error

Table 6 presents the means and standard deviations for angular error. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the three-way interaction between torso, hand and visual field, $\chi^2(2) = 6.08, p = .05$. For this interaction effect, degrees of freedom were corrected for using the Greenhouse-Geisser estimate of sphericity ($\epsilon = .65$). All other variables and interactions met the sphericity assumption. The repeated measures ANOVA revealed that there was no significant effect ($p > .05$) of torso orientation, hand position, or visual field on the angular error, nor was there any significant interactions. Testing the standardised residuals for normality, again, all six groups met the normality assumption ($p > .05$), e.g. $W(20) = .96, p = .54$. **Figure 12D** shows the mean angular error values plotted by condition and by visual field.

Table 6

Mean Angular Error (radians) for Left and Right Visual Field Targets by Condition

Condition	Left VF		Right VF	
	Means	SD	Means	SD
TLHL	-.07	.28	-.01	.17
TLHR	.03	.29	-.10	.20
TCHL	-.01	.23	-.06	.17
TCHR	.01	.33	-.12	.43
TRHL	.03	.21	-.09	.21
TRHR	.05	.24	-.14	.30

Cartesian Error

Table 7 presents the means and standard deviations for Cartesian error. Mauchly’s test of sphericity indicated that all variables and interactions met the assumption of sphericity ($p > .05$). The repeated measures ANOVA revealed that the main effect of torso position, $F(2,18) = .23, p = .80$, and the main effect of hand placement, $F(1,9) = .15, p = .71$, were non-significant. Therefore, similar to amplitude error, when visual field is disregarded and all twelve targets are considered, Cartesian error was not significantly greater or smaller for hand left compared to hand right, or between the left, centre and right torso orientations. Unlike amplitude error, the main effect of visual field was marginally significant, with a large effect size, $F(1,9) = 5.74, p = .04, \eta_p^2 = .39$. Examining the post hoc test, the mean Cartesian error for right visual field targets ($M = 199$ pixels) was significantly greater than the mean Cartesian error for left visual field targets ($M = 174$ pixels), irrespective of condition. The highly significant interaction between torso position and visual field found for amplitude error was also present for Cartesian error, $F(2,18) = 14.72, p < .001, \eta_p^2 = .62$, with a similar effect size. The interaction between hand position and visual field, however, was non-significant, $F(1,9) = 1.29, p = .29, \eta_p^2 = .13$.

Table 7

Mean Cartesian Error (pixels) for Left and Right Visual Field Targets by Condition

Condition	Left VF		Right VF	
	Means	SD	Means	SD
TLHL	166	45.3	219	65.9
TLHR	164	18.3	213	81.8
TCHL	154	58.7	219	66.3
TCHR	170	97.7	213	66.9
TRHL	185	94.1	162	58
TRHR	204	81.1	166	75.8

Figure 12E illustrates the interaction effect of torso and visual field, this time on saccade Cartesian error. The torso centre control condition presented the same relationship as before, with right visual field error significantly greater on average ($M = 216$ pixels) than left visual field error ($M = 162$ pixels), $t(19) = -3.95, p = .001$. When the torso was rotated rightward, there was the repeat pattern of left visual field mean error increasing ($M = 194$ pixels), whilst right visual field mean error reduced ($M = 164$ pixels). Again, these changes

resulting from a rightward rotation were large enough for the relationship between the two visual fields to reverse, with the mean Cartesian error of right targets becoming significantly smaller than the mean Cartesian error of left targets, $t(19) = 2.15, p = .05$. The leftward rotation did not quite elicit the exact same effect as with amplitude error. The mean Cartesian error for right visual field targets did increase as before ($M = 216$ pixels), but the Cartesian error for left visual field targets also increased slightly ($M = 165$ pixels), causing the difference between the two to actually decrease in significance, $t(19) = -3.01, p < .01$.

Testing the standardised residuals for normality, two of the six groups met the normality assumption ($p > .05$) but four groups violated the assumption, with one p value of .03 and three values of $p < .01$. It is generally agreed that the related groups of a repeated measures ANOVA need only be approximately normally distributed, since the test is quite robust to violations of this assumption (Lewis, 1993). The p value of .03, therefore, was not a major concern. However, the three more highly significant results prompted the use of a non-parametric test to check for any type I or type II errors.

Using Friedman's test as the non-parametric equivalent of the repeated measures ANOVA, there was a non-significant effect for torso position, $\chi^2(2) = 1.55, p = .46$, hand position, $\chi^2(1) = .27, p = .61$, and visual field, $\chi^2(1) = 1.07, p = .30$. The interaction effect of visual field and torso position was significant, $\chi^2(5) = 18, p < .01$, but the interaction of visual field and hand position was non-significant, $\chi^2(3) = 4.72, p = .19$. The non-parametric test therefore produced the same outcome as the parametric test, except for the effect of visual field, which went from being marginally significant to non-significant. It was not essential to be certain of this type I error since the effect of visual field was not the effect we were interested in, i.e. it wasn't as a result of the experimental manipulation.

Considering the significant interaction effect of torso and visual field, post hoc analysis using the Wilcoxon signed-rank test revealed that, for torso centre, saccades towards right visual field targets were less accurate ($Mdn = 197$ pixels) than saccades made towards left targets ($Mdn = 142$ pixels). This difference was highly significant, $Z = -3.21, p = .001$. For torso left, rightward saccades were also less accurate ($Mdn = 206$ pixels) than leftward saccades ($Mdn = 170$ pixels), but the difference was slightly less significant, $Z = -2.58, p = .01$. Finally, for torso right, the relationship reversed, with leftward saccades generating significantly greater error ($Mdn = 169$ pixels) than rightward saccades ($Mdn = 190$ pixels), $Z = -2.17, p = .03$. Both the relationships between the left and right visual field for each

torso position, and the degree of significance, were a replication of the results from the paired samples t-tests. **Figure 12F** illustrates the Cartesian error mean values for left and right visual field saccades, for all hand and torso position combinations.

Reaction Time

Table 8 presents the means and standard deviations for reaction time. Similar to the output for angular error, Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the three-way interaction between torso, hand and visual field, $\chi^2(2) = 7.41, p = .03$. As before, the degrees of freedom were corrected for using the Greenhouse-Geisser estimate of sphericity ($\epsilon = .62$). All other variables met the sphericity assumption.

Table 8

Mean Reaction Time (milliseconds) for Left and Right Visual Field Targets by Condition

Condition	Left VF		Right VF	
	Means	SD	Means	SD
TLHL	342	68.2	391	70.5
TLHR	340	66.4	401	98.8
TCHL	362	71.1	404	58.6
TCHR	370	128	412	134
TRHL	349	83.2	370	54.5
TRHR	361	85.6	369	96

The repeated measures ANOVA revealed that, as with amplitude and Cartesian error, the interaction between torso position and visual field was the only effect to reach significance, $F(2,18) = 3.78, p = .04, \eta_p^2 = .30$. For reaction time, this effect was not as highly significant or as large ($p < .001$ and $\eta_p^2 > .5$, for both amplitude and Cartesian error). **Figure 12G** illustrates the interaction of torso position with visual field for the measure of reaction time. Looking at the whole graph, there is not the inverse diagonal relationship seen repeatedly with the amplitude and Cartesian error variables. Instead, there is a shallow inverted 'U' shape to the results. For all three torso positions, saccades towards left visual field targets were faster than saccades towards right visual field targets. For torso centre, the mean reaction time of leftward saccades was 366 milliseconds (ms) whilst the mean reaction time of rightwards saccades was significantly higher at 408 ms,

$t(19) = -2.20, p = .04$. When the torso was rotated to the left, the mean reaction time for leftward saccades decreased ($M = 341$ ms), as did the mean reaction time for rightward saccades ($M = 396$ ms), although to a lesser degree (down by 12 ms as opposed to 25 ms), increasing the significance of the difference between the two, $t(19) = -3.340, p < .01$. Again, when the torso was rotated to the right, the mean reaction time for leftward saccades decreased in comparison to the control condition ($M = 355$ ms), as did the mean reaction time for rightward saccades ($M = 370$ ms), but to a much greater degree this time (down by 38 ms as opposed to 11 ms), causing the difference between the two visual fields to become non-significant, $t(19) = -.89, p = .38$.

Testing the standardised residuals for normality, one of the six groups (right visual field, torso centre, hand left) violated the assumption, $W(20) = .87, p = .01$. Again, to be certain of any important type I or type II errors, we compared the results from the repeated measures ANOVA with the results from Friedman's test. In contrast to the results for Cartesian error, running the non-parametric version of the means comparison test did make a considerable difference for reaction time. There was no evidence of any type I errors, since the single significant effect (the torso by visual field interaction) found using the repeated measures ANOVA was also found using the Friedman's test, $\chi^2(5) = 12.2, p = .03$. Post hoc analysis using the Wilcoxon signed-rank test revealed the same visual field relationships as the t-test, with leftward saccades faster than rightward saccades for torso left (left $Mdn = 341$ ms; right $Mdn = 381$ ms), torso centre (left $Mdn = 340$ ms; right $Mdn = 407$ ms), and torso right (left $Mdn = 338$ ms; right $Mdn = 363$ ms). The degree of significance for each pair was also very similar, although not identical. The difference between visual fields for torso left was similarly highly significant, $Z = -3.14, p < .01$, the difference between visual fields for torso right was similarly non-significant, $Z = -.60, p = .55$, but the difference between visual field for torso centre, which had been significant ($p < .05$) was marginally non-significant, $Z = -1.79, p = .07$.

Friedman's test did however reveal evidence for two type II errors. Where there had been no significant effect before, there was a significant interaction effect of hand with visual field found, $\chi^2(3) = 9.08, p = .03$. The Wilcoxon signed-rank test revealed that, for hand left, saccades towards left visual field targets were significantly faster ($Mdn = 325$ ms) than saccades towards right visual field targets ($Mdn = 383$ ms), $Z = -2.48, p = .01$. For hand right, again, leftward saccades were faster ($Mdn = 345$ ms) than rightward saccades ($Mdn = 365$), but this time the difference was only marginally significant, $Z = -1.94, p = .05$. Since there is no hand centre condition, the nature of the *change* to mean reaction time

following the manipulation of hand position cannot be defined, however, the results do resemble the torso left and torso right conditions; the relationship between the visual fields is the same for both conditions but the degree of significance is higher for the leftward condition. **Figure 12H** illustrates this emerging interaction effect, displaying left and right visual field *median* reaction time values for the two hand position conditions.

The second previously non-significant effect found was an effect of visual field, $\chi^2(1) = 6.67, p = .01$. As is clear from any of the reaction time figures, the Wilcoxon signed-ranks test revealed that saccades towards left visual field targets were significantly faster in general (*Mdn* = 341 ms) than saccades towards right visual field targets (*Mdn* = 380 ms), $Z = -3.19, p = .001$. Like before, this was of less importance, since an effect of visual field cannot be attributed to the manipulation. The effects of hand position and torso position across visual fields remained non-significant ($p > .05$). **Figure 12I** illustrates the reaction time mean values for left and right visual field saccades, for all hand and torso position combinations.

Discussion

Before discussing the effect of the experimental manipulation, it is worthwhile discussing the results at torso centre. For all four measures, the mean for right visual field targets was significantly greater than the mean for left visual field targets. This result was unexpected given that our right-handed subjects were likely right-eye dominant. The entirely positive range of values for mean amplitude error meant there was a strong tendency for saccades to be hypermetric, which is normal for saccades less than 15° (Becker, 1989). With angular error, although a significant effect of visual field did not emerge, it would appear from the column chart that saccade endpoints were quite consistently anti-clockwise from the target within right visual field and clockwise from the target in left visual field (i.e. saccades tended to land above targets). The fact that these hypermetric and ‘above target’ tendencies appear to be exaggerated within the right hemifield might reflect reduced left hemisphere inhibition (in comparison to the right hemisphere inhibition imposed by left hemisphere) described by Kinsbourne (1977) as the cause of a rightward orientation bias present from birth. This does not explain the significantly greater mean reaction time for right visual field targets at torso centre. This result is perhaps attributable to the dominance of the right hemisphere in spatial working memory (McCarthy et al., 1996; Whitehouse & Bishop, 2009). Each hemisphere is responsible for initiating saccades in the contralateral direction (Wauschkuhn et al., 1998) and so, if the remembered location of the target is held in right hemisphere throughout the 3-second delay period, this information would have to cross the corpus callosum for the production of a rightward saccade, but not for the production of a leftward saccade.

The most important outcome of the present study was the repeated emergence of an interaction between the experimental manipulation and visual field. The interaction effect of visual field with torso position was very highly significant for amplitude and Cartesian error, and moderately significant for reaction time. The interaction effect of visual field with hand position was significant for reaction time after using the non-parametric test, and only marginally non-significant for amplitude error. For amplitude and Cartesian error, the pattern of results was always the same; as hypothesised, rotating the torso or moving the hand reduced the mean error for ipsilateral targets whilst increasing the mean error for contralateral targets. For leftward manipulations, this caused the existing disparity between left and right visual field to increase. For rightward manipulations, the disparity decreased, sometimes to the point of the relationship reversing. When the amplitude and Cartesian error means for all six conditions are displayed together on a column chart, it would appear

that the effect of rotating the torso and the effect of moving the hand could be additive. Presented like this, it is possible to see an inverse diagonal relationship, with right visual field error highest for ‘torso left, hand left’ and left visual field error highest for ‘torso right, hand right’.

This same inverse diagonal relationship can be seen clearly in the Cartesian error results (and very nearly in the amplitude error results) of the 2015 Podmore study. In this study, the interaction effect of torso with visual field did not reach significance. Within conditions, the difference in error between left and right visual field saccades was also smaller than in the present study; t-tests revealed that the difference was only significant for amplitude error, and marginally non-significant for Cartesian error, at torso right. It is not possible to say whether the increase in participants (from 6 to 10), the increase in rotation (from 20° to 90°), or both were responsible for the increase in significance of the present results. The introduction of the two hand positions also meant that twice as much data was collected at each torso position. The ipsilateral-to-rotation bias found in the Paschke et al. (2015) study is slightly less comparable but still relevant; torso rotation still led to an improvement in the ipsilateral hemifield, albeit in speed of stimulus perception and not saccade accuracy. The bias found by Paschke and colleagues was only significant for left handers and only following rightward rotation, as has been the case in other rotation studies (Hasselbach-Heitzeg & Reuter-Lorenz, 2002). This study found significant results for both left and right rotations, and despite participants being right-handed.

One interpretation is that torso rotation primes participants for a saccade in the same direction as rotation, transforming the hemifield containing the rotated torso into a dorsal stream action space. In a study by Jackson, Miall, and Balslev (2010), participants were provided with a proprioceptive signal in the form of a brief lateral force to the arm, before being asked to detect a near-threshold visual target. Detection rate increased when the proprioceptive signal provided a valid spatial cue and decreased when it provided an invalid spatial cue. In the present study, proprioceptive input from the neck muscles following rotation, and arm muscles following hand placement, would have provided a valid spatial cue for targets ipsilateral to the manipulation and an invalid spatial cue for targets contralateral to the manipulation. Participants changed position after every trial to prevent the decay of this signal (i.e. to prevent participants from habituating to the position). A valid spatial cue could improve saccade accuracy by allocating attentional resources to the ipsilateral hemifield. Essentially, the cue demands attention, attention grants a processing priority, and a processing priority enhances performance. The ability of

a proprioceptive cue to recruit visual attention has been demonstrated through its successful use as a neglect treatment (Bailey, Riddoch, & Crome, 2002; Eskes, Butler, McDonald, Harrison, & Phillips, 2003; Johannsen, Ackermann, & Karnath, 2003; Kerkhoff, 2003; Schindler, Kerkhoff, Karnath, Keller, & Goldenberg, 2002) and attention has been shown to increase performance, with respect to both latency (Posner, 1980; Posner, Snyder, & Davidson, 1980) and accuracy (Balz & Hock, 1997; Bashinski & Bacharach, 1980; Kurylo, Reeves, & Scharf, 1996; Luck et al., 1994; Shaw & Shaw, 1977) in a wide range of visual tasks.

Although there is good evidence for a performance-related effect of proprioceptive cuing, and although torso rotation would provide such a cue, there is one factor that could possibly prevent this interpretation from being appropriate for the present paradigm, and that is the systematic presentation of saccade targets. Attention works like a zoom lens, reducing the amount of information, the amount of scanning, and the amount of noise, resulting in faster and more efficient processing. Other proposed mechanisms for the performance enhancing effect of attention include an effect on decisional processes, such as the adoption of a more liberal criterion or a greater weighting on attended information (Kinchla, Chen, & Evert, 1995; Palmer, 1994), a signal enhancement effect, whereby sensory neurons produce a stronger and more selective response to attended stimuli than they do unattended stimuli (Reynolds, Pasternak, & Desimone, 1997; Treue & Maunsell, 1996), and a contraction of receptive fields around the attended area, leading to enhanced spatial resolution (Yeshurun & Carrasco, 1999). A left or right torso rotation or hand placement would reduce the field of attention by 50%, preparing the participant for a target within one hemifield or the other. However, in the present study, target presentation was systematic and so participants would know exactly where to expect a target and their attention would be focused accordingly, making it difficult to see how restricting attention to one hemifield would be of any added benefit. We would therefore change this interpretation from the idea of torso rotation as a spatial cue, to the idea that torso rotation can increase the salience of targets on one side. For target salience to have a performance enhancing effect on already attended stimuli, the mechanism(s) underlying this effect would need a graded quality i.e. even stronger signals, even greater decisional weight, or even smaller receptive fields.

An alternative interpretation is that, as a result of body-centred or even mixed body reference frames, torso rotation causes the subjective centre to deviate left and right from objective centre (the fixation cross), changing the length of the spatial vector between

target and reference point. When the torso is forward-facing, left and right targets are equidistant relative to both the objective and subjective centre. However, when the torso is rotated left, the spatial vector between subjective centre and left visual field targets is shortened, whilst the spatial vector between subjective centre and right visual field targets is lengthened. When the torso is rotated to the right, the reverse happens. We propose that, despite the actual distance between the target and the saccade's starting location remaining the same, a shorter *coded* distance might afford greater accuracy. Evidence from neglect studies can support the existence of a trunk-anchored subjective centre, its ability to be manipulated, and its ability to affect behaviour. For example, Karnath et al. (1991) reported that neglect patients with right hemisphere damage were slower to react to left visual field targets, but that a leftward trunk rotation could alleviate the lag. This suggested to the authors that the impairment was contralesional with respect to trunk space, not absolute space, and that the rotation had shifted the subjective centre enough for left targets to become ipsilesional within this coordinate frame. Evidence for a relationship between accuracy and 'coded distance' (the spatial vector between target and reference point, as opposed to the movement vector between target and effector) is harder to find, however.

An effect of retinal eccentricity on accuracy is probably the closest thing to have been reported. Studies involving a saccade task, search task, and pointing task (with movement amplitude held constant) have all demonstrated that as target distance increases relative to the retina, accuracy decreases (Bock, 1986; Carrasco, Evert, Chang, & Katz, 1995; Pouget, Ducom, et al., 2002; Scialfa & Joffe, 1998). In the context of a retinal-centred reference frame, this could reflect an effect of coded distance. The more obvious interpretation is that targets were sensed using vision, and visual acuity deteriorates for increasingly peripheral targets. The fovea and the periphery offer different levels of spatial resolution for a number of reasons; there are more receptor cells in the fovea, more high spatial frequency channels, greater contrast sensitivity, fewer receptor cells converging onto a single ganglion cell, and smaller receptive fields (De Valois & De Valois, 1988). This leaves the proposed relationship between accuracy and coded distance rather unsupported. However, the idea is not implausible. Vision occurs when a photoreceptor is stimulated by a visual stimulus entering the receptive field, and one of the reasons why spatial resolution is poor in the periphery is because receptive fields increase in size with distance from the fovea (i.e. the centre of the sensory surface). Similarly, spatial representation occurs when a spatially tuned neuron is stimulated by a stimulus entering the receptive field. If the receptive fields of spatially tuned neurons also increase in size, this time with distance from the centre of the reference frame, then coded distance might well have an effect on

movement accuracy because the larger more distant receptive fields would only offer crude information about the target's spatial location.

Both interpretations can be applied to the results of the hand manipulation. The effects of torso position and hand position appear to be additive, which could indicate mixed coding. In the presence of mixed body/hand reference frames, both the torso and hand would have an independent influence (or 'pulling power') on subjective centre, leading to a larger deviation and therefore greater change to spatial vector length for same-direction manipulations, and a smaller deviation and therefore lesser change to spatial vector length for opposing manipulations. It is also straightforward to appreciate how two congruent proprioceptive signals would increase the salience of targets in one hemifield more so than two incongruent proprioceptive signals (the torso on one side and the hand on the other). Without a hand centre condition, we cannot say for definite that error decreased for ipsilateral targets and increased for contralateral targets as a result of the two hand placements. In all other ways, the results echoed the results of the torso manipulation, with greater disparity between visual fields at hand left, lower mean error for left visual field targets at hand left than hand right, and lower mean error for right visual field targets at hand right than hand left. Despite these similarities, it must be reiterated that the interaction effect of hand position with visual field was non-significant for Cartesian error and marginally non-significant for amplitude error. The partial eta squared value for the marginal result indicated a large effect size, and so it is possible that this effect would reach significance following additional testing. Still, the effect of torso rotation on saccade kinematics would appear to be stronger than the effect of hand positioning. If the effect is in fact due to the presence of mixed body/hand reference frames, perhaps this indicates an unbalanced mixed reference frame more strongly influenced by the position of the torso. It is also possible that the smaller effect of hand position reflects the weaker manipulation. For the torso manipulation, we were able to rotate the chair a full 90°, and were able to do so equally on both sides, whereas, with the hand manipulation, the hand left position could only be a short distance from centre due to participant flexibility.

Unlike amplitude and Cartesian error, the interaction effect of visual field with torso position, and visual field with hand position, was non-significant for angular error. This is not surprising considering the very low levels of angular error across conditions; targets were spaced 30° apart and yet mean angular error ranged from 0.6° to 8°. Our only suggestion is that angular accuracy was facilitated by the participant's strong familiarity with the clock face layout. The fact that participants will have viewed a twelve-point circle

with 30° intervals countless times might have meant that they were able to formulate an educated estimation of target angle, even before seeing and coding the spatial location of the stimulus. This stored spatial representation would not help with estimating target eccentricity, however. French and Richards (1993) demonstrated a clock face schema by showing participants an image of a clock and asking them to draw it from memory. In the majority of drawings, the number four was represented as 'IV' (the roman numeral presented on clocks but not elsewhere) and not 'IIII', as it was on the image.

Whereas angular error produced no significant results at all, there were three significant results for reaction time after non-parametric testing. The first was a significant effect of visual field, with faster reaction times for leftward saccades. As discussed, this could reflect the role of right hemisphere in spatial working memory. The second was a significant interaction effect of visual field with torso position. This interaction effect did not present the same pattern of results as amplitude and Cartesian error, and was less significant in comparison. Not finding the same pattern of results for this temporal variable (or not finding an effect at all) does not refute the interpretation given for the spatial variables, because having less information about target location at the time of encoding would not influence the speed with which saccades are initiated. The fact that a significant effect *has* emerged would suggest either something different or something additional is at play. As with Cartesian and amplitude error, reaction time decreased for ipsilateral targets following rotation, however, reaction time for contralateral targets also decreased. Interestingly, although rotation led to faster reactions on both sides, reaction time decreased more for left visual field targets than right visual field targets at torso left, and decreased more for right visual field targets than left visual field targets at torso right. The decrease in reaction time for contralateral targets does not agree with previous studies that have measured reaction time in response to torso rotations. Grubb and Reed (2002) reported that leftward rotation significantly reduced reaction times for left-sided targets and significantly increased reaction times for right-sided targets, although only when targets were preceded by an invalid visual cue on the opposite side. Hasselbach-Heitzeg and Reuter-Lorenz (2002) reported that rightward rotation significantly reduced reaction times for right-sided targets, whilst increasing reaction times for left-sided targets by a marginally non-significant amount. In both of these studies, participants did not know where the target would appear and were required to indicate target onset with a button press. Therefore, the perceptual component of this reaction time measure varied between conditions, whereas the perceptual component in the present study (the disappearance of the distractor dots) did not, meaning the difference in reaction times can be attributed to

the motor component. At present, we do not have a thorough explanation for the reaction time results. We suspect that, for this variable, the effect of the manipulation is in motor cortex and not PPC, perhaps with proprioceptive input from the neck and arm instigating some sort of ‘readiness’ in the motor neurons of saccade regions.

The third significant result for reaction time was an interaction effect of visual field with hand position. This interaction followed the same pattern as the marginally non-significant visual field by hand position interaction found for amplitude error; within both conditions, right visual field error was greater than left visual field error, but left visual field error was greater for hand right than hand left and right visual field error was greater for hand left than hand right, creating a greater disparity between visual fields at hand left. Again, without a hand centre condition, we cannot know how reaction time has changed as a result of the manipulation. Placing the hand to the left and right may have reduced reaction times for both hemifields but to different degrees, the same as torso rotation. Alternatively, it may have reduced reaction time for ipsilateral targets whilst increasing reaction time for contralateral targets, the same as the Cartesian and amplitude error results. It is not possible to say. A hand centre condition *was* included in the pilot study, raising the number of trials to nine. The feedback from this pilot study was that the eye tracker became uncomfortable, the back began to ache, and the repetitive saccadic movements became tiring on the eyes. For this reason, we reduced the number of conditions to six by removing the hand centre position.

4. Future Research

Functional MRI

Voxels entered into the analysis were selected on the basis of two parameters – a coherence threshold and a manually defined ROI. The shape, size and location of this ROI was determined by anatomical landmarks. An alternative approach would be to use multi-variate pattern analysis (MVPA). MVPA distinguishes patterns of neural activity by analysing fMRI activity as vectors in high-dimensional representational space (Haxby, Connolly, & Guntupalli, 2014). Each column of the matrix represents a single voxel and each row is a response vector i.e. the activity resulting from a specific stimulus or at a specific time point. Taken together, the profile of responses is called the tuning function. Then, in a classification process, the high-dimensional representational space is divided up into categories or classes of response vectors by decision boundaries formed using

machine learning methods. This process of developing decision rules is performed on the proportion of data referred to as the training data, before being put to the test on independent test data. Most classification analyses are linear, for example, one-nearest-neighbour (Haxby et al., 2001), support vector machine (SVM) classifiers (Cox & Savoy, 2003), and linear discriminant analysis (LDA) (O'Toole, Jiang, Abdi, & Haxby, 2005). In terms of the present research, MVPA could determine 1) which voxels are responding to the onset of the saccade targets, and 2) of these voxels, which do and don't respond differently following a change in hand position. The class of response vectors responding to both the correct stimuli and the moving hand would essentially form the 'ROI', except the advantage of this method is that these voxels need not be tightly clustered at one location.

In addition to this alternative analysis method, we would encourage future fMRI studies testing hand position to adopt flat, rested hand placements. Some of the activity in the present study will have been associated to the gripping action of the hand as it held onto the cylindrical bars of the apparatus. The process of averaging across two different hand positions should also be avoided. If it is not possible to collect a sufficient amount of data at each hand position, lateral and depth manipulations should be tested independently within separate scanning sessions or separate studies. When testing changes in hand depth, it would make sense for the stimulus display to be three dimensional. This way, it would be possible to observe the effect of hand-anchored receptive fields in the midsagittal plane. Three dimensional stimuli suitable for the scanner bore include LED target boards and virtual reality (VR) environments.

Eye Tracking

The present behavioural experiment could be extended to include left hand manipulations and binocular eye tracking. Ideally, no more than six trials should be included in any one sitting, based on participant feedback. To introduce additional conditions, testing could be divided into sessions, or hand and torso manipulations tested independently. In addition, Paschke et al. (2015) highlighted the importance of taking individual differences in functional laterality into account when investigating the effects of torso rotation, and so future studies should test and group participants by handedness and ocular dominance. Future studies should also introduce a control for the hand manipulation, whether this be a central hand placement on the desk or a neutral resting position on the knee or chair. It should be noted that the systematic change to the polar angle of saccade endpoints is

necessary for the functional MRI paradigm but not the behavioural paradigm. Future replications of the eye tracking experiment could repeat the same manipulations and measures of performance, but with an alternative target layout and a random order of presentation. Before addressing any of the suggested changes, we intend to collect more data using the exact same procedure. It will be interesting to see if the existing patterns retain their shape and whether the marginal hand by visual field interaction increases or decreases in significance.

5. Implications

Brain machine interface (BMI) technologies are able to extract and decode command signals from the brain and use these signals to drive an external actuator such as a neural prosthetic limb. Such systems restore function to paralysed and amputee patient groups. Invasive BMI techniques include cortically implanted microelectrode arrays that record the activity of single neurons (Carmena et al., 2003; Ganguly & Carmena, 2009; Hochberg et al., 2006; Velliste, Perel, Spalding, Whitford, & Schwartz, 2008), and electrocorticography (ECoG) - electrodes placed on the surface of the brain to record the concerted activity of neuronal populations (Leuthardt, Schalk, Wolpaw, Ojemann, & Moran, 2004). Research on neural prosthetics has largely focused on the primary motor cortex however, recent studies have concluded that PPC is a good candidate for neuroprosthetic applications in humans, providing the same trajectory signals offered by motor cortex, in addition to cognitive variables such as goal encoding (Aflalo et al., 2015). These cognitive variables offer a number of advantages: 1) they can lead to a very rapid readout of the intended movement, 2) they can represent sequential movements, 3) they can improve the accuracy of trajectory decoding, 4) and they can allow for the operation of two prosthetics from one hemisphere, due to the bimanual representation of the limbs (Hauschild et al., 2012). However, the ability to successfully use PPC for prosthetic applications partially rests on our understanding of spatial coordinate schemes in this region. For accurate use, the trajectory signals for the reaching prosthetic would need to be in ‘hand-centred’ coordinates (object location with respect to the robotic limb). This would require PPC to represent ‘hand’ position in the absence of proprioceptive input, or at least before the introduction of skin prostheses and other mechanoreceptors (Kim et al., 2014). Studies using dummy hands have demonstrated that this is possible (Graziano, 1999; Makin et al., 2007). Secondly, since the input to the prosthetic will bypass many of the coordinate transformations that allow for explicit higher-order coding within motor cortex, it is important to investigate locations of pure hand-centred representation within human PPC.

6. Conclusions

In every condition across both experiments, participants performed the exact same task and targets remained at the same locations within retinal and head-centred space. If the spatially tuned neurons encoding target location were doing so within a retinal or head-centred coordinate frame, there would be no reason to expect any significant differences in average phase or performance. However, significant differences *were* found. In the neuroimaging experiment, there was a significant difference in median phase between left and right hand positions for the left and right hemispheres of participant one and left hemisphere of participant two, and a significant difference in median phase between near and far hand positions for the left and right hemispheres of both participants. In the eye tracking experiment, there was a significant interaction effect of torso position with visual field for amplitude error, Cartesian error and reaction time, a significant interaction effect of hand position with visual field for reaction time, a marginally non-significant interaction effect of hand position with visual field for amplitude error, and a significant effect of visual field for reaction time. Although the fMRI results were significant, we would like to develop the analysis and collect more data before presenting this research as evidence for hand-centred coding. The results of the eye-tracking experiment were much more consistent and can be interpreted in the context of body and hand-centred coding. Behavioural research like this cannot explicitly demonstrate pure body and hand-centred coordinate frames in the way that invasive techniques can, but the aim of the present study was to move away from non-human primate research and develop techniques that can explore spatial representation within the human brain. The evidence for non-retinal coordinate schemes within PPC continues to grow, along with an appreciation for the variety, the complexity, and possibly even the fluidity with which our brain represents space.

Appendix A - Invitation Letter (fMRI)

Title of project

Trunk and Hand-Centred Spatial Coordinate Frames

Lead researcher

Dr. Jason D. Connolly, Department of Psychology, Durham University, UK
Telephone (office): 0191-334-0474; email: j.d.connolly@durham.ac.uk

What we investigate

The main investigation concerns how the brain is functionally organised for representing 'around the clock' eye movements and whether or not these maps are modulated by different starting hand locations. There is much evidence to suggest that adjacent areas of eye movement targets are mapped onto adjacent areas of the actual cortical tissue. To address this, we will use functional Magnetic Resonance Imaging (fMRI), which is a non-invasive technique that allows the scientist to examine blood flow to brain areas that are presumably underlying the computations at hand. Such topographic maps then provide a platform with which to address issues related to spatial awareness, such as whether areas of the brain code visual stimuli relative to the eyes, the hand or even the world. We will test different starting hand positions. This will provide evidence as to which areas of the healthy human brain code for depth in space. This will then optimise brain-computer interface decoding of neural signal in parietal cortex.

What participants would do

- Participate in one fMRI scanning session (approx. 1.5 hours in duration)

During the fMRI session, participants will look at dots in sequence, and they will be asked to move their eyes toward the remembered location of the flashed dot. In pseudo-randomised scan runs, participants will have their hand placed at different static locations within the scanner.

- Participate in an information/familiarisation session (approx. 15 minutes in duration).

The information session should take place before the day of the study. In this session we would explain the specific experimental task and allow the participant to familiarise themselves with the scanner, should they wish.

Where the study takes place

The fMRI scanning session will be conducted at the James Cook University Hospital in Middlesbrough on a 3-Tesla, whole-body MRI system. The information session will be conducted at the Centre for Vision and Visual Cognition, where the Department of Psychology houses a 0-Tesla (mock) scanner.

Transportation of participants

We would arrange for the transportation of the participant by accompanying the person (if desired) to and from the research facilities.

Benefit to participants

A direct benefit of the study to the participants is that they will learn about how the human brain works and will contribute their own time to further neural prosthetic brain-computer interfaces to assist patients with paralysis. If there is interest from sides of the participants, we will also provide literature on this topic. In addition to a verbal de-briefing, participants will receive any publication, press release or other public or scientific communication related to this work. In addition, if there is interest, we will personally discuss the results with them (in person, e-mail, or phone; whatever is feasible).

Appendix B – Participant Information Sheet (fMRI)

Trunk and Hand-Centred Spatial Coordinate Frames

Invitation

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take the time to read the following information carefully. Talk to others about the study if you wish. Ask me if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of the study?

Our work is based on the idea that understanding the brain areas that generate eye movements combined with different static hand positions will provide insight into higher brain functions (such as spatial awareness). Furthermore, identifying the areas that underlie spatial awareness will assist in the development of devices (so-called brain-computer interfaces) designed to assist patients suffering from paralysis by allowing them to communicate with computers via thought alone. We will ask you to look at the former (remembered location) of a flashed visual target. You will be asked to move your eyes as quickly as possible to this remembered location. The cue for you to make this movement will be the disappearance of a cross that will be located at the centre of the screen. You will be asked to do this with your hand/arm at different static locations within the scanner. These tasks will be done with concurrent brain imaging which is effectively harmless. By collecting these data, we will be able to identify key brain regions involved in movement control and higher cognition. These insights will further advance brain-computer interface algorithms necessary to provide patients with paralysis with enhanced independence, by providing for example, that they can use their thoughts to control computer cursors (to provide but one example).

Why have I been chosen?

We are seeking to recruit 4 adults with these characteristics:

- They are eighteen years old or older.
- They have no problems with their sight or hearing (glasses and contact lenses are fine).
- They are right-handed

Do I have to take part?

Taking part in the research is entirely voluntary. It is up to you to decide whether or not to take part. If you do, you will be given this information sheet to keep and be asked to sign a consent form. You are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

If you choose to take part in the experiment we will arrange a convenient time for you to come over to the CVVC so that we can take you through the experimental procedure and check that you are comfortable with the confines of the scanner. If you are happy to continue, we can confirm the date and time for the 1.5-hour scanning session at the James Cook University Hospital. Magnetic Resonance Imaging (MRI) is a technique that can non-invasively examine brain activation. Participants lie in a magnetic field, and radiofrequency pulses are used to generate images of the brain. The strength of the magnetic field used by the Siemens scanner at the James Cook University Hospital is 3 Tesla. The experiment needs you to lie still in the scanner while making eye movements towards remembered peripheral targets (or cues) that will be presented on the screen. The scanning session

includes one structural scan (five minutes duration) and 12 functional scans (approx. 4.5 minutes duration each). You will do 3 functional scans (or runs) at each of the 4 hand positions, and each scan/run will contain 5 laps 'around the clock'. These five laps will either be clockwise or anticlockwise. You will be able to rest between runs/scans. We thank you for considering participating: your participation will contribute to gaining fundamental new knowledge about brain function and assistive technologies to provide paralysed patients with enhanced independence.

What are the other possible disadvantages and risks of taking part?

Research at Durham University and at the James Cook University Hospital is planned and conducted in a way that minimizes the risk of harm to participants. Given that MRI works at a high magnetic field, producing high sound levels, a set of procedures is used to minimize any stress or discomfort and to ensure your safety.

- Claustrophobia and feelings of isolation while lying inside the scanner will be reduced by providing full time communication with the operator via button press;
- High sound levels during MRI will be reduced by using earplugs;
- To help you to lie still during the experiment your head will be positioned using soft flexible foam;
- Feelings of disequilibrium or mild nausea on entering or leaving the magnetic field will be minimized by moving the magnet bed very slowly and by asking you to keep your eyes closed.

Please note that the use of a high magnetic field imposes several restrictions. No ferromagnetic material must be present during scanning, so we cannot scan some people (e.g. those with metal implants including dental braces, pacemakers, cochlear or brainstem implants, or those who have any other surgical implants containing metal).

What will happen if I don't want to carry on with the study?

You are free to withdraw from the study at any time and without giving an explanation. This will have no prejudicial effect whatever on your academic standing. However, please note that we are obliged to keep the data for 10 years, and that we would normally analyse them unless you request us not to.

What if there is a problem?

This study has been approved by the Research Ethics Committee of Durham University, but if you have a concern about any aspect of it, you should speak with the researchers, who will do their best to answer your questions: Dr. Jason D. Connolly (office phone number: 0191-334-0474; e-mail: j.d.connolly@durham.ac.uk) or Professor Charles A. Heywood (office phone number: 0191-334-0447; e-mail: c.a.heywood@durham.ac.uk). If you remain unhappy and wish to complain formally, you can do this through the complaints procedures of Durham University. Details can be obtained from: <http://www.dur.ac.uk/gsu/appeals/> Durham University takes pride and care in ensuring that no harm, or risk of harm, occurs to participants in research. In the event that something does go wrong and you are harmed during the research study and this is due to someone's negligence, then you may have grounds for a legal action for compensation against the University of Durham University (each is responsible for its own employees).

Will my taking part in the study be kept confidential?

Any information you give me, and all of the measurements that we collect from you (MRI images) will be confidential. We shall comply with the terms of the Data Protection Act 1988. We shall store the information and the measurements in anonymous computer files and in locked filing cabinets. We shall store names and addresses separately from other data. As well as using your data in the present study, we may also combine them with data gathered in future studies. Only the following person will know your contact details: **Dr J. D Connolly**. No names will be used when the research is written up. We shall keep your

data for 10 years and will then destroy it securely. With the approval of the Research Ethics Committee of Durham University, other researchers may be allowed access to your data, for use in research or teaching. Those researchers will be allowed access to your data in anonymous form only. We are not qualified to interpret brain images for clinical purposes. If we suspect that an image of your brain reveals a possible problem, we shall inform your GP (family doctor) who may then contact you and advise you. If you do not want us to do this, then you should not agree to take part in the study.

Who is directing and funding the research?

Dr. Jason Connolly and Prof. Charles Heywood, housed in the Department of Psychology at Durham University, direct the study.

The results will be used to write scientific publications, and will be available to participants by contacting Jason Connolly at the following number 0191-334-0474 or e-mail address: j.d.connolly@durham.ac.uk.

Appendix C – Durham University General Consent Form

TITLE OF PROJECT:

Trunk and Hand-Centred Spatial Coordinate Frames

(The participant should complete the whole of this sheet himself/herself)

*Please cross out
as necessary*

Have you read the Participant Information Sheet? YES / NO

Have you had an opportunity to ask questions and to discuss the study? YES / NO

Have you received satisfactory answers to all of your questions? YES / NO

Have you received enough information about the study and the Intended uses of, and access arrangements to, any data which you supply ? YES / NO

Were you given enough time to consider whether you want to participate? YES/NO

Who have you spoken to?

Dr/Mr/Mrs/Ms/Prof.....

Do you consent to participate in the study? YES/NO

Do you understand that you are free to withdraw from the study:

- * at any time and
- * without having to give a reason for withdrawing and
- * without any adverse result of any kind? YES / NO

Signed **Date**

(NAME IN BLOCK LETTERS)

Appendix D – Durham University MRI Consent Form

I confirm that I consent to my MRI scans, and the results obtained, being used for research purposes run at the James Cook University Hospital and approved by the South Tees Hospital NHS Trust and Durham University MRI Facility. I confirm that I have been fully informed about the nature of the procedures and have completed the safety questionnaires.

The South Tees Hospital NHS Trust and Durham University MRI Facility is not a clinical diagnostic facility and as such does not routinely inspect all scans for anomalies. However, from time to time an anomaly is observed on MRI scan. South Tees Hospital NHS Trust and Durham University MRI Facility can only indicate that further advice might be sought. The presence or absence of an anomalous scan is not an indication of the presence or absence of pathology.

If an anomalous observation were made South Tees Hospital NHS Trust and Durham University MRI Facility **must** inform your General Practitioner.

Please note: If you prefer not to have your General Practitioner's practice informed South Tees Hospital NHS Trust and Durham University MRI Facility will regrettably be unable to scan you. If you are not currently registered with a UK General Practitioner or do not know the contact address of your current General Practitioner South Tees Hospital NHS Trust and Durham University MRI Facility will be unable to scan you.

I consent to my General Practitioner's practice being contacted if an anomaly is observed and I understand that the South Tees Hospital NHS Trust and Durham University MRI Facility is not offering diagnostic advice and that no clinical advice will be offered.

Please Tick One: YES NO

Participant Name: ID number
.....

Telephone number:

E-mail:

Signature:

Date:

General Practitioner's Practice Address:

.....
.....
.....
.....
.....

Appendix E - South Tees Hospital NHS Trust and Durham University MRI Screening Form

So that we can safely proceed with the examination, we need to check that there are no factors that would prevent you from having an MRI scan. **Please complete this questionnaire and bring it with you.** A member of staff will check through it with you when you arrive

QUESTION	YES	NO	COMMENTS
Do you have a cardiac pacemaker or an implanted cardioverter defibrillator?			
Do you have an artificial heart valve?			
Do you have severe heart disease (including susceptibility to arrhythmias)?			
Do you have an intracranial aneurysm clip?			
Do you have a programmable intracranial shunt?			
Do you have Meniere's disease?			
Do you have epilepsy or diabetes or a thermoregulatory condition?			
Do you have a cochlear implant, other type of hearing aid or false teeth?			
Do you have an implanted neurostimulator or medicine delivery pump?			
Have you ever been injured by a metallic foreign body which was not removed (e.g., bullet, BB, shrapnel)?			
Have you had any surgery on your head, spine or chest?			
Are you wearing an artificial limb?			
Do you wear a medicine patch (e.g. nicotine, contraceptive, or angina)?			
Have you ever had any operations, which may have involved the use of metallic pins, plates, screws, artificial limbs or ocular implants?			
Do you have dental work other than fillings?			
To the best of your knowledge, do you have impaired renal function or are you awaiting a liver transplant?			
Have you ever worked with metal (grinding, fabricating, welding, etc.) or ever had an injury to the eye involving a metallic object (e.g., metallic slivers, shavings)?			
Do you have any tattoos or permanent eyeliner?			
Do you have any body piercings that cannot be removed?			
Female participants:			
Is there any possibility that you may be pregnant?			

Are you currently breast-feeding?			
Do you have a contraceptive intrauterine device (IUD)?			

Due to the strong magnetic field, watches, jewellery, body piercings, hearing aids, credits cards, mobile phones, belts with metal buckles, and pagers are not permitted in the scanner. Neither are loose metallic objects such as pens, coins, hair clips, cigarette lighters, metallic denture plates. Please empty your pockets.

I have removed the following items from my body (Items will be kept securely in the Room):	
Any jewellery, wrist watch or belts	
Any body piercings	
Any hairpins or clips	
Wallet and credit cards	
Coins, pens and cigarette lighter	
Anything else from any of your pockets	
Female participants:	
Underwire bra	

Signed

Date.....

Witnessed By (Member of staff).....

Date.....

The day of the scan:

- If applicable, remember to wear contact lenses instead of glasses.
- Do not drink excessive amounts of liquid, especially caffeine (a diuretic -- an fMRI session seems much longer with a full bladder!).
- Do not wear any shirts with metal around the head (e.g., pullovers with zippers). Metal buttons and zippers on pants are okay. Do not use any hairclips and be prepared to remove jewellery.
- For women, if possible, do not wear an underwire bra (the metal can throw off the magnetic field). Sports bras are usually good and we keep a baggy sweater around if you want to wear it.
- If possible avoid mascara (can contain metal flakes), hair gel (can throw off magnet signal) and wet hair.
- Make sure you know where you are going to meet the experimenter and what time you are expected to show up.

If anything comes up such that you cannot make your scheduled time, notify the experimenter *as soon as possible*: 3T MRI at James Cook University Hospital: 01642 282799

While in the scanner:

- If you notice anything vaguely uncomfortable before you get rolled into the scanner, please tell the experimenter. Things that are slightly uncomfortable at the start become excruciating by the end.
- Try not to change head or body position during a scan (while the magnet is beeping). If the head moves, it creates artifacts that are usually difficult if not impossible to fix. The position of body parts in the magnetic field distorts it. So if you cross your legs, scratch your head, open your mouth, or shift your posture, it can lead to artifacts even if your brain doesn't move. We try to keep runs as short as possible (ideally under 7 minutes) so that you can stay in the same position the whole time.
- Between scans (when the magnet is not beeping), you can change your body position, scratch, swallow, etc. **BUT** do your best not to do anything that will move your head from its original position.
- Swallowing can lead to head motion artifacts. If you can avoid swallowing during a scan, the data quality will be better. If trying not to swallow makes you gag or swallow suddenly, then it's best to just swallow normally.
- Try to stay relaxed throughout the session. If you tense up at the beginning of a scan, your head can drift as you settle down.
- If you notice anything weird with the stimuli (e.g., they're upside down or you can't see the display or the screen saver comes on partway through a scan) or have problems with the task (e.g., make mistakes, fall asleep), be sure to tell the experimenter after the scan in which it happened.

1 = torso left, hand left
2 = torso left, hand right
3 = torso centre, hand left

4 = torso centre, hand right
5 = torso right, hand left
6 = torso right, hand right

Set #1

p1=1, p2=4, p3=2, p4=3, p5=5, p6=6

Set #2

p1=2, p2=3, p3=1, p4=4, p5=6, p6=5

Set #3

p1=5, p2=6, p3=4, p4=1, p5=2, p6=3

Set #4

p1=5, p2=1, p3=3, p4=2, p5=4, p6=6

Set #5

p1=3, p2=1, p3=2, p4=5, p5=6, p6=4

Set #6

p1=6, p2=4, p3=5, p4=2, p5=3, p6=1

Set #7

p1=5, p2=4, p3=2, p4=1, p5=6, p6=3

Set #8

p1=5, p2=6, p3=3, p4=2, p5=1, p6=4

Set #9

p1=5, p2=6, p3=1, p4=3, p5=2, p6=4

Set #10

p1=5, p2=1, p3=4, p4=2, p5=3, p6=6

Trunk and Hand-Centred Spatial Coordinate Frames

Invitation

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take the time to read the following information carefully. Ask me if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of the study?

When your brain codes the location of, for example, the coffee mug you wish to pick up, it uses a reference frame. For example, if it employs an eye-centred reference frame, it would be coding the location of the coffee mug **relative** to your eye. We are going to investigate types of reference frames by having you do a task that will require your brain to code the location of targets presented on the screen. You will complete this task with your hand at different positions and your body at different rotations. What this means is that the targets will always stay in the same position relative to your eye, but will be made different relative to your hand and to your torso. We will be taking a measure of your reaction time and various measures of error (we will compare where the target is to where you actually move your eyes to on the screen i.e. how far off you were) and we will be looking to see if these measure differ across the different hand and body positions. These insights into spatial reference frames will help towards improving advanced brain-computer interface algorithms that drive assistive devices (such as robotic limbs) used by patients with severe motor paralysis.

What will happen to me if I take part?

First, the experimenter will fit the eye tracker to your head and will adjust the cameras. You will then have to go through what's called a calibration procedure. All this requires you to do is to follow a white dot around the screen with your eyes. This procedure checks that the eye tracker is tracking your pupil movements accurately. You may have to do this numerous times before the accuracy is at an acceptable level. We will then begin the experiment. You will perform the experimental task a total of 9 times. Before each round, I will ask you to move your hand to one of three positions on the desk in front of you, and twist your chair to one of three positions as well. The task requires you to stare at a white cross in the centre of the screen. If you imagine a clock face on the screen, a white 'target' dot is going to appear at each of the 12 locations on the clock face, successively and in a clockwise direction. When the dot appears, it is important that you don't move your eyes to look at it. Just stay focused on the centre cross and hold in your memory, as best you can, the location of the target. The target will then disappear and will be replaced by a ring of what we call distracter dots. You must stay looking at the centre whilst these distracter dots are on the screen. As soon as the distracter dots disappear, you must look to the position on the screen where the target had been, and then back to the centre, **as quickly as you can**. You also have to be **as accurate as you can**, so don't move your eyes so fast that they stop nowhere near the point you are aiming for. Pretty much as soon as your eyes make it back to the centre, the next target will appear, and the whole procedure will repeat. You are going to go 'around the clock' five times, so that's 60 targets into total (12x5) until the screen will say 'done!' and we will move you to the next hand and body position.

Why have I been chosen?

We are seeking to recruit around 15 adults with these characteristics:

- They are eighteen years old or older.
- They have no problems with their sight or hearing (glasses are fine).

- They are right-handed

Do I have to take part?

Taking part in the research is entirely voluntary. It is up to you to decide whether or not to take part. If you do, you will be given this information sheet to keep and be asked to sign a consent form. You are still free to withdraw at any time and without giving a reason.

What are the possible disadvantages and risks of taking part?

There are no risks associated with taking part in this study. It is possible that you could feel discomfort, either as result of the body positions you will be holding, or because the eye tracker feels too tight around your head. If this happens, inform the experimenter – they will be able to do something to fix the discomfort with minimal disruption to the experiment.

What will happen if I don't want to carry on with the study?

You are free to withdraw from the study at any time and without giving an explanation. This will have no prejudicial effect whatever on your academic standing. However, please note that we are obliged to keep the data for 10 years, and that we would normally analyse them unless you request us not to.

What if there is a problem?

This study has been approved by the Research Ethics Committee of Durham University, but if you have a concern about any aspect of it, you should speak with the researchers, who will do their best to answer your questions: Dr. Jason D. Connolly (office phone number: 0191-334-0474; e-mail: j.d.connolly@durham.ac.uk) or Professor Charles A. Heywood (office phone number: 0191-334-0447; e-mail: c.a.heywood@durham.ac.uk). If you remain unhappy and wish to complain formally, you can do this through the complaints procedures of Durham University. Details can be obtained from: <http://www.dur.ac.uk/gsu/appeals/> Durham University takes pride and care in ensuring that no harm, or risk of harm, occurs to participants in research. In the event that something does go wrong and you are harmed during the research study and this is due to someone's negligence, then you may have grounds for a legal action for compensation against the University of Durham University (each is responsible for its own employees).

Will my taking part in the study be kept confidential?

Any information you give and all of the measurements that we collect from you will be confidential. We shall comply with the terms of the Data Protection Act 1988. We shall store the information and the measurements in anonymous computer files and in locked filing cabinets. We shall store names and addresses separately from other data. As well as using your data in the present study, we may also combine them with data gathered in future studies. Only the following person will know your contact details: **Dr J. D Connolly**. No names will be used when the research is written up. We shall keep your data for 10 years and will then destroy it securely. With the approval of the Research Ethics Committee of Durham University, other researchers may be allowed access to your data, for use in research or teaching. Those researchers will be allowed access to your data in anonymous form only.

Who is directing and funding the research?

Dr. Jason Connolly and Prof. Charles Heywood, housed in the Department of Psychology at Durham University, direct the study.

The results will be used to write scientific publications, and will be available to participants by contacting Jason Connolly at the following number 0191-334-0474 or e-mail address: j.d.connolly@durham.ac.uk.

We thank you for considering participating: your participation will contribute to gaining fundamental new knowledge about brain function and assistive technologies to provide paralysed patients with enhanced independence.

References

- Aflalo, T., Kellis, S., Klaes, C., Lee, B., Shi, Y., Pejsa, K., . . . Andersen, R. A. (2015). Neurophysiology. Decoding motor imagery from the posterior parietal cortex of a tetraplegic human. *Science*, *348*(6237), 906-910. doi:10.1126/science.aaa5417
- Andersen, R. A. (1995). Encoding of intention and spatial location in the posterior parietal cortex. *Cereb Cortex*, *5*(5), 457-469.
- Andersen, R. A., Essick, G. K., & Siegel, R. M. (1985). Encoding of spatial location by posterior parietal neurons. *Science*, *230*(4724), 456-458.
- Andersen, R. A., Hwang, E. J., & Mulliken, G. H. (2010). Cognitive neural prosthetics. *Annu Rev Psychol*, *61*, 169-190, C161-163. doi:10.1146/annurev.psych.093008.100503
- Andersen, R. A., & Mountcastle, V. B. (1983). The influence of the angle of gaze upon the excitability of the light-sensitive neurons of the posterior parietal cortex. *J Neurosci*, *3*(3), 532-548.
- Andersen, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annu Rev Neurosci*, *20*, 303-330. doi:10.1146/annurev.neuro.20.1.303
- Andersen, R. A., Snyder, L. H., Li, C. S., & Stricanne, B. (1993). Coordinate transformations in the representation of spatial information. *Curr Opin Neurobiol*, *3*(2), 171-176.
- Avillac, M., Deneve, S., Olivier, E., Pouget, A., & Duhamel, J. R. (2005). Reference frames for representing visual and tactile locations in parietal cortex. *Nat Neurosci*, *8*(7), 941-949. doi:10.1038/nn1480
- Bailey, M. J., Riddoch, M. J., & Crome, P. (2002). Treatment of visual neglect in elderly patients with stroke: a single-subject series using either a scanning and cueing strategy or a left-limb activation strategy. *Phys Ther*, *82*(8), 782-797.
- Balz, G. W., & Hock, H. S. (1997). The effect of attentional spread on spatial resolution. *Vision Res*, *37*(11), 1499-1510.
- Bashinski, H. S., & Bacharach, V. R. (1980). Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations. *Percept Psychophys*, *28*(3), 241-248.
- Batista, A. P., Buneo, C. A., Snyder, L. H., & Andersen, R. A. (1999). Reach plans in eye-centered coordinates. *Science*, *285*(5425), 257-260.
- Becker, W. (1989). The neurobiology of saccadic eye movements. Metrics. *Rev Oculomot Res*, *3*, 13-67.
- Bock, O. (1986). Contribution of retinal versus extraretinal signals towards visual localization in goal-directed movements. *Exp Brain Res*, *64*(3), 476-482.
- Bosco, A., Breveglieri, R., Hadjidimitrakis, K., Galletti, C., & Fattori, P. (2016). Reference frames for reaching when decoupling eye and target position in depth and direction. *Sci Rep*, *6*, 21646. doi:10.1038/srep21646
- Boussaoud, D., & Bremmer, F. (1999). Gaze effects in the cerebral cortex: reference frames for space coding and action. *Exp Brain Res*, *128*(1-2), 170-180.
- Brotchie, P. R., Andersen, R. A., Snyder, L. H., & Goodman, S. J. (1995). Head position signals used by parietal neurons to encode locations of visual stimuli. *Nature*, *375*(6528), 232-235. doi:10.1038/375232a0
- Brozzoli, C., Gentile, G., & Ehrsson, H. H. (2012). That's near my hand! Parietal and premotor coding of hand-centered space contributes to localization and self-attribution of the hand. *J Neurosci*, *32*(42), 14573-14582. doi:10.1523/JNEUROSCI.2660-12.2012
- Bruce, C. J., & Goldberg, M. E. (1985). Primate frontal eye fields. I. Single neurons discharging before saccades. *J Neurophysiol*, *53*(3), 603-635.
- Buneo, C. A., Jarvis, M. R., Batista, A. P., & Andersen, R. A. (2002). Direct visuomotor transformations for reaching. *Nature*, *416*(6881), 632-636. doi:10.1038/416632a

- Carmena, J. M., Lebedev, M. A., Crist, R. E., O'Doherty, J. E., Santucci, D. M., Dimitrov, D. F., . . . Nicolelis, M. A. (2003). Learning to control a brain-machine interface for reaching and grasping by primates. *PLoS Biol*, *1*(2), E42.
doi:10.1371/journal.pbio.0000042
- Carrasco, M., Evert, D. L., Chang, I., & Katz, S. M. (1995). The eccentricity effect: target eccentricity affects performance on conjunction searches. *Percept Psychophys*, *57*(8), 1241-1261.
- Chen, J., & Niemeier, M. (2014). Do head-on-trunk signals modulate disengagement of spatial attention? *Exp Brain Res*, *232*(1), 147-157. doi:10.1007/s00221-013-3727-6
- Cohen, Y. E., & Andersen, R. A. (2000). Reaches to sounds encoded in an eye-centered reference frame. *Neuron*, *27*(3), 647-652.
- Cohen, Y. E., & Andersen, R. A. (2002). A common reference frame for movement plans in the posterior parietal cortex. *Nat Rev Neurosci*, *3*(7), 553-562.
doi:10.1038/nrn873
- Colby, C. L. (1998). Action-oriented spatial reference frames in cortex. *Neuron*, *20*(1), 15-24.
- Connolly, J. D., Podmore, J. J., Kentridge, R. W., & Cavina-Pratesi, C. (in preparation). *Body-centred coordinates in parietal cortex*. Department of Psychology. Durham University.
- Connolly, J. D., Vuong, Q. C., & Thiele, A. (2015). Gaze-dependent topography in human posterior parietal cortex. *Cereb Cortex*, *25*(6), 1519-1526.
doi:10.1093/cercor/bht344
- Constantin, A. G., Wang, H., Martinez-Trujillo, J. C., & Crawford, J. D. (2007). Frames of reference for gaze saccades evoked during stimulation of lateral intraparietal cortex. *J Neurophysiol*, *98*(2), 696-709. doi:10.1152/jn.00206.2007
- Cox, D. D., & Savoy, R. L. (2003). Functional magnetic resonance imaging (fMRI) "brain reading": detecting and classifying distributed patterns of fMRI activity in human visual cortex. *Neuroimage*, *19*(2 Pt 1), 261-270.
- Critchley, M. (1953). *The Parietal Lobes*. New York: Hafner Publishing.
- De Valois, R. L., & De Valois, K. K. (1988). *Spatial vision*. . New York: Oxford University Press.
- DeSouza, J. F., Dukelow, S. P., Gati, J. S., Menon, R. S., Andersen, R. A., & Vilis, T. (2000). Eye position signal modulates a human parietal pointing region during memory-guided movements. *J Neurosci*, *20*(15), 5835-5840.
- Dijkerman, H. C., & de Haan, E. H. (2007). Somatosensory processes subserving perception and action. *Behav Brain Sci*, *30*(2), 189-201; discussion 201-139.
doi:10.1017/S0140525X07001392
- Duhamel, J. R., Bremmer, F., Ben Hamed, S., & Graf, W. (1997). Spatial invariance of visual receptive fields in parietal cortex neurons. *Nature*, *389*(6653), 845-848.
doi:10.1038/39865
- Edin, B. B., & Johansson, N. (1995). Skin strain patterns provide kinaesthetic information to the human central nervous system. *J Physiol*, *487*(1), 243-251.
- Eskes, G. A., Butler, B., McDonald, A., Harrison, E. R., & Phillips, S. J. (2003). Limb activation effects in hemispatial neglect. *Arch Phys Med Rehabil*, *84*(3), 323-328.
doi:10.1053/apmr.2003.50012
- Fattori, P., Breveglieri, R., Bosco, A., Gamberini, M., & Galletti, C. (2017). Vision for prehension in the medial parietal cortex. *Cereb Cortex*, *27*(2), 1149-1163.
- Fernandez-Ruiz, J., Goltz, H. C., DeSouza, J. F., Vilis, T., & Crawford, J. D. (2007). Human parietal "reach region" primarily encodes intrinsic visual direction, not extrinsic movement direction, in a visual motor dissociation task. *Cereb Cortex*, *17*(10), 2283-2292. doi:10.1093/cercor/bhl137
- Ferraina, S., Brunamonti, E., Giusti, M. A., Costa, S., Genovesio, A., & Caminiti, R. (2009). Reaching in depth: hand position dominates over binocular eye position in

- the rostral superior parietal lobule. *J Neurosci*, 29(37), 11461-11470.
doi:10.1523/JNEUROSCI.1305-09.2009
- Fiehler, K., Schutz, I., & Henriques, D. Y. (2011). Gaze-centered spatial updating of reach targets across different memory delays. *Vision Res*, 51(8), 890-897.
doi:10.1016/j.visres.2010.12.015
- Fishman, R. S. (1997). Gordon Holmes, the cortical retina, and the wounds of war. *Documenta ophthalmologica*, 93(1-2), 9-28.
- Fogassi, L., Gallese, V., di Pellegrino, G., Fadiga, L., Gentilucci, M., Luppino, G., . . . Rizzolatti, G. (1992). Space coding by premotor cortex. *Exp Brain Res*, 89(3), 686-690.
- French, C. C., & Richards, A. (1993). Clock this!: An everyday example of a schema-driven error in memory. *British Journal of Psychology*, 84(2), 249-253.
- Galletti, C., Battaglini, P. P., & Fattori, P. (1993). Parietal neurons encoding spatial locations in craniotopic coordinates. *Exp Brain Res*, 96(2), 221-229.
- Ganguly, K., & Carmena, J. M. (2009). Emergence of a stable cortical map for neuroprosthetic control. *PLoS Biol*, 7(7), e1000153.
doi:10.1371/journal.pbio.1000153
- Gnadt, J. W., Andersen, R. A., & Blatt, G. J. (1986). Spatial, memory, and motor-planning properties of saccade-related activity in the lateral intraparietal area (LIP) of macaque. . *Society For Neuroscience Abstracts*, 12, 454.
- Graziano, M. S. (1999). Where is my arm? The relative role of vision and proprioception in the neuronal representation of limb position. *Proc Natl Acad Sci U S A*, 96(18), 10418-10421.
- Graziano, M. S., & Gross, C. G. (1998). Spatial maps for the control of movement. *Curr Opin Neurobiol*, 8(2), 195-201.
- Graziano, M. S., Yap, G. S., & Gross, C. G. (1994). Coding of visual space by premotor neurons. *Science*, 266(5187), 1054-1057.
- Grubb, J. D., & Reed, C. L. (2002). Trunk orientation induces neglect-like lateral biases in covert attention. *Psychol Sci*, 13(6), 553-556. doi:10.1111/1467-9280.00497
- Hadjidimitrakis, K., Bertozzi, F., Breveglieri, R., Fattori, P., & Galletti, C. (2014). Body-centered, mixed, but not hand-centered coding of visual targets in the medial posterior parietal cortex during reaches in 3D space. *Cereb Cortex*, 24(12), 3209-3220. doi:10.1093/cercor/bht181
- Hadjidimitrakis, K., Dal Bo, G., Breveglieri, R., Galletti, C., & Fattori, P. (2015). Overlapping representations for reach depth and direction in caudal superior parietal lobule of macaques. *J Neurophysiol*, 114(4), 2340-2352.
doi:10.1152/jn.00486.2015
- Hasselbach-Heitzeg, M. M., & Reuter-Lorenz, P. A. (2002). Egocentric body-centered coordinates modulate visuomotor performance. *Neuropsychologia*, 40(11), 1822-1833.
- Hauschild, M., Mulliken, G. H., Fineman, I., Loeb, G. E., & Andersen, R. A. (2012). Cognitive signals for brain-machine interfaces in posterior parietal cortex include continuous 3D trajectory commands. *Proc Natl Acad Sci U S A*, 109(42), 17075-17080. doi:10.1073/pnas.1215092109
- Haxby, J. V., Connolly, A. C., & Guntupalli, J. S. (2014). Decoding neural representational spaces using multivariate pattern analysis. *Annu Rev Neurosci*, 37, 435-456.
doi:10.1146/annurev-neuro-062012-170325
- Haxby, J. V., Gobbini, M. I., Furey, M. L., Ishai, A., Schouten, J. L., & Pietrini, P. (2001). Distributed and overlapping representations of faces and objects in ventral temporal cortex. *Science*, 293(5539), 2425-2430. doi:10.1126/science.1063736
- Henriques, D. Y., Klier, E. M., Smith, M. A., Lowy, D., & Crawford, J. D. (1998). Gaze-centered remapping of remembered visual space in an open-loop pointing task. *J Neurosci*, 18(4), 1583-1594.

- Hochberg, L. R., Serruya, M. D., Friehs, G. M., Mukand, J. A., Saleh, M., Caplan, A. H., . . . Donoghue, J. P. (2006). Neuronal ensemble control of prosthetic devices by a human with tetraplegia. *Nature*, *442*(7099), 164-171. doi:10.1038/nature04970
- Hubel, D. H., & Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *J Physiol*, *160*, 106-154.
- Hwang, E. J., & Andersen, R. A. (2009). Brain control of movement execution onset using local field potentials in posterior parietal cortex. *J Neurosci*, *29*(45), 14363-14370. doi:10.1523/JNEUROSCI.2081-09.2009
- Jackson, C. P., Miall, R. C., & Balslev, D. (2010). Spatially valid proprioceptive cues improve the detection of a visual stimulus. *Exp Brain Res*, *205*(1), 31-40. doi:10.1007/s00221-010-2330-3
- Jay, M. F., & Sparks, D. L. (1987). Sensorimotor integration in the primate superior colliculus. I. Motor convergence. *J Neurophysiol*, *57*(1), 22-34.
- Johannsen, L., Ackermann, H., & Karnath, H. O. (2003). Lasting amelioration of spatial neglect by treatment with neck muscle vibration even without concurrent training. *J Rehabil Med*, *35*(6), 249-253.
- Karnath, H. O. (1994). Subjective body orientation in neglect and the interactive contribution of neck muscle proprioception and vestibular stimulation. *Brain*, *117* (Pt 5), 1001-1012.
- Karnath, H. O., Christ, K., & Hartje, W. (1993). Decrease of contralateral neglect by neck muscle vibration and spatial orientation of trunk midline. *Brain*, *116* (Pt 2), 383-396.
- Karnath, H. O., Fetter, M., & Dichgans, J. (1996). Ocular exploration of space as a function of neck proprioceptive and vestibular input--observations in normal subjects and patients with spatial neglect after parietal lesions. *Exp Brain Res*, *109*(2), 333-342.
- Karnath, H. O., Schenkel, P., & Fischer, B. (1991). Trunk orientation as the determining factor of the 'contralateral' deficit in the neglect syndrome and as the physical anchor of the internal representation of body orientation in space. *Brain*, *114* (Pt 4), 1997-2014.
- Kerkhoff, G. (2003). Modulation and rehabilitation of spatial neglect by sensory stimulation. *Prog Brain Res*, *142*, 257-271. doi:10.1016/S0079-6123(03)42018-9
- Kim, J., Lee, M., Shim, H. J., Ghaffari, R., Cho, H. R., Son, D., . . . Kim, D. H. (2014). Stretchable silicon nanoribbon electronics for skin prosthesis. *Nat Commun*, *5*, 5747. doi:10.1038/ncomms6747
- Kinchla, R. A., Chen, Z., & Evert, D. (1995). Precue effects in visual search: data or resource limited? *Percept Psychophys*, *57*(4), 441-450.
- Kinsbourne, M. (1977). Hemi-neglect and hemisphere rivalry. *Adv Neurol*, *18*, 41-49.
- Kinsbourne, M. (1993). Orientational bias model of unilateral neglect: evidence from attentional gradients within hemispace *Unilateral neglect: Clinical and experimental studies* (pp. 63-86): Psychology Press.
- Konen, C. S., & Kastner, S. (2008). Representation of eye movements and stimulus motion in topographically organized areas of human posterior parietal cortex. *J Neurosci*, *28*(33), 8361-8375. doi:10.1523/JNEUROSCI.1930-08.2008
- Kurylo, D. D., Reeves, A., & Scharf, B. (1996). Expectancy of line segment orientation. *Spat Vis*, *10*(2), 149-162.
- Lackner, J. R., & DiZio, P. A. (2000). Aspects of body self-calibration. *Trends Cogn Sci*, *4*(7), 279-288.
- Leuthardt, E. C., Schalk, G., Wolpaw, J. R., Ojemann, J. G., & Moran, D. W. (2004). A brain-computer interface using electrocorticographic signals in humans. *J Neural Eng*, *1*(2), 63-71. doi:10.1088/1741-2560/1/2/001
- Luck, S. J., Hillyard, S. A., Mouloua, M., Woldorff, M. G., Clark, V. P., & Hawkins, H. L. (1994). Effects of spatial cuing on luminance detectability: psychophysical and

- electrophysiological evidence for early selection. *J Exp Psychol Hum Percept Perform*, 20(4), 887-904.
- Makin, T. R., Holmes, N. P., & Zohary, E. (2007). Is that near my hand? Multisensory representation of peripersonal space in human intraparietal sulcus. *J Neurosci*, 27(4), 731-740. doi:10.1523/JNEUROSCI.3653-06.2007
- McCarthy, G., Puce, A., Constable, R. T., Krystal, J. H., Gore, J. C., & Goldman-Rakic, P. (1996). Activation of human prefrontal cortex during spatial and nonspatial working memory tasks measured by functional MRI. *Cereb Cortex*, 6(4), 600-611.
- Medendorp, W. P., Goltz, H. C., Crawford, J. D., & Vilis, T. (2005). Integration of target and effector information in human posterior parietal cortex for the planning of action. *J Neurophysiol*, 93(2), 954-962. doi:10.1152/jn.00725.2004
- Medendorp, W. P., Goltz, H. C., Vilis, T., & Crawford, J. D. (2003). Gaze-centered updating of visual space in human parietal cortex. *J Neurosci*, 23(15), 6209-6214.
- Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annu Rev Psychol*, 42, 135-159. doi:10.1146/annurev.ps.42.020191.001031
- Mullette-Gillman, O. A., Cohen, Y. E., & Groh, J. M. (2005). Eye-centered, head-centered, and complex coding of visual and auditory targets in the intraparietal sulcus. *J Neurophysiol*, 94(4), 2331-2352. doi:10.1152/jn.00021.2005
- Mullette-Gillman, O. A., Cohen, Y. E., & Groh, J. M. (2009). Motor-related signals in the intraparietal cortex encode locations in a hybrid, rather than eye-centered reference frame. *Cereb Cortex*, 19(8), 1761-1775. doi:10.1093/cercor/bhn207
- Mulliken, G. H., Musallam, S., & Andersen, R. A. (2008). Decoding trajectories from posterior parietal cortex ensembles. *J Neurosci*, 28(48), 12913-12926. doi:10.1523/JNEUROSCI.1463-08.2008
- Neppi-Modona, M., Auclair, D., Sirigu, A., & Duhamel, J. R. (2004). Spatial coding of the predicted impact location of a looming object. *Curr Biol*, 14(13), 1174-1180. doi:10.1016/j.cub.2004.06.047
- O'Toole, A. J., Jiang, F., Abdi, H., & Haxby, J. V. (2005). Partially distributed representations of objects and faces in ventral temporal cortex. *J Cogn Neurosci*, 17(4), 580-590. doi:10.1162/0898929053467550
- Palmer, J. (1994). Set-size effects in visual search: the effect of attention is independent of the stimulus for simple tasks. *Vision Res*, 34(13), 1703-1721.
- Paschke, K., Kagan, I., Wustenberg, T., Bahr, M., & Wilke, M. (2015). Trunk rotation affects temporal order judgments with direct saccades: Influence of handedness. *Neuropsychologia*, 79(Pt A), 123-137. doi:10.1016/j.neuropsychologia.2015.10.031
- Pertsov, Y., Avidan, G., & Zohary, E. (2011). Multiple reference frames for saccadic planning in the human parietal cortex. *J Neurosci*, 31(3), 1059-1068. doi:10.1523/JNEUROSCI.3721-10.2011
- Pesaran, B., Nelson, M. J., & Andersen, R. A. (2006). Dorsal premotor neurons encode the relative position of the hand, eye, and goal during reach planning. *Neuron*, 51(1), 125-134. doi:10.1016/j.neuron.2006.05.025
- Pisierchia, V., Breveglieri, R., Hadjidimitrakis, K., Bertozzi, F., Galletti, C., & Fattori, P. (2017). Mixed body/hand reference frame for reaching in 3D space in macaque parietal area PEc. *Cerebral Cortex*, 27(3), 1976-1990.
- Podmore, J. J. (2015). *Effects of torsal rotation with fixed eye and head position on saccade kinematics*. (Psychology BSc), Durham University.
- Posner, M. I. (1980). Orienting of attention. *Q J Exp Psychol*, 32(1), 3-25.
- Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *J Exp Psychol*, 109(2), 160-174.
- Pouget, A., Dayan, P., & Zemel, R. (2000). Information processing with population codes. *Nat Rev Neurosci*, 1(2), 125-132. doi:10.1038/35039062

- Pouget, A., Deneve, S., & Duhamel, J. R. (2002). A computational perspective on the neural basis of multisensory spatial representations. *Nat Rev Neurosci*, 3(9), 741-747. doi:10.1038/nrn914
- Pouget, A., Ducom, J. C., Torri, J., & Bavelier, D. (2002). Multisensory spatial representations in eye-centered coordinates for reaching. *Cognition*, 83(1), B1-11.
- Reynolds, J., Pasternak, T., & Desimone, R. (1997). Attention increases contrast sensitivity of cells in macaque area V4 *Investigative Ophthalmology & Visual Science* (Vol. 38, pp. 3206). Philadelphia Lippincott-Raven Publications.
- Ro, T., Rorden, C., Driver, J., & Rafal, R. (2001). Ipsilesional biases in saccades but not perception after lesions of the human inferior parietal lobule. *J Cogn Neurosci*, 13(7), 920-929. doi:10.1162/089892901753165836
- Robertson, I. H., & Marshall, J. C. (1993). *Unilateral Neglect: Clinical and Experimental Studies*: Psychology Press.
- Rorden, C., Karnath, H. O., & Driver, J. (2001). Do neck-proprioceptive and caloric-vestibular stimulation influence covert visual attention in normals, as they influence visual neglect? *Neuropsychologia*, 39(4), 364-375.
- Rubens, A. B. (1985). Caloric stimulation and unilateral visual neglect. *Neurology*, 35(7), 1019-1024.
- Russo, G. S., & Bruce, C. J. (1994). Frontal eye field activity preceding aurally guided saccades. *J Neurophysiol*, 71(3), 1250-1253.
- Salinas, E., & Abbott, L. F. (1996). A model of multiplicative neural responses in parietal cortex. *Proc Natl Acad Sci U S A*, 93(21), 11956-11961.
- Salinas, E., & Sejnowski, T. J. (2001). Gain modulation in the central nervous system: where behavior, neurophysiology, and computation meet. *Neuroscientist*, 7(5), 430-440. doi:10.1177/107385840100700512
- Schindler, I., Kerkhoff, G., Karnath, H. O., Keller, I., & Goldenberg, G. (2002). Neck muscle vibration induces lasting recovery in spatial neglect. *J Neurol Neurosurg Psychiatry*, 73(4), 412-419.
- Schluppeck, D., Curtis, C. E., Glimcher, P. W., & Heeger, D. J. (2006). Sustained activity in topographic areas of human posterior parietal cortex during memory-guided saccades. *J Neurosci*, 26(19), 5098-5108. doi:10.1523/JNEUROSCI.5330-05.2006
- Schluppeck, D., Glimcher, P., & Heeger, D. J. (2005). Topographic organization for delayed saccades in human posterior parietal cortex. *J Neurophysiol*, 94(2), 1372-1384. doi:10.1152/jn.01290.2004
- Schwartz, B. L., & Krantz, J. H. (2014). *Sensation and Perception*. US: Sage Publications.
- Scialfa, C. T., & Joffe, K. M. (1998). Response times and eye movements in feature and conjunction search as a function of target eccentricity. *Percept Psychophys*, 60(6), 1067-1082.
- Sereno, M. I., & Huang, R. S. (2006). A human parietal face area contains aligned head-centered visual and tactile maps. *Nat Neurosci*, 9(10), 1337-1343. doi:10.1038/nn1777
- Sereno, M. I., Pitzalis, S., & Martinez, A. (2001). Mapping of contralateral space in retinotopic coordinates by a parietal cortical area in humans. *Science*, 294(5545), 1350-1354. doi:10.1126/science.1063695
- Shaw, M. L., & Shaw, P. (1977). Optimal allocation of cognitive resources to spatial locations. *J Exp Psychol Hum Percept Perform*, 3(2), 201-211.
- Shenoy, K. V., Meeker, D., Cao, S., Kureshi, S. A., Pesaran, B., Buneo, C. A., . . . Andersen, R. A. (2003). Neural prosthetic control signals from plan activity. *Neuroreport*, 14(4), 591-596. doi:10.1097/01.wnr.0000063250.41814.39
- Silver, M. A., & Kastner, S. (2009). Topographic maps in human frontal and parietal cortex. *Trends Cogn Sci*, 13(11), 488-495. doi:10.1016/j.tics.2009.08.005
- Silver, M. A., Ress, D., & Heeger, D. J. (2005). Topographic maps of visual spatial attention in human parietal cortex. *J Neurophysiol*, 94(2), 1358-1371. doi:10.1152/jn.01316.2004

- Smeets, J. B., van den Dobbelsteen, J. J., de Grave, D. D., van Beers, R. J., & Brenner, E. (2006). Sensory integration does not lead to sensory calibration. *Proc Natl Acad Sci U S A*, *103*(49), 18781-18786. doi:10.1073/pnas.0607687103
- Snijders, H. J., Holmes, N. P., & Spence, C. (2007). Direction-dependent integration of vision and proprioception in reaching under the influence of the mirror illusion. *Neuropsychologia*, *45*(3), 496-505. doi:10.1016/j.neuropsychologia.2006.01.003
- Snyder, L. H. (2000). Coordinate transformations for eye and arm movements in the brain. *Curr Opin Neurobiol*, *10*(6), 747-754.
- Snyder, L. H., Brotchie, P. R., & Andersen, R. A. (1993). World-centred encoding of location in posterior parietal cortex of monkey. *Society For Neuroscience Abstracts*, *19*, 770.
- Stark, L., & Bridgeman, B. (1983). Role of corollary discharge in space constancy. *Percept Psychophys*, *34*(4), 371-380.
- Steinbach, M. J. (1987). Proprioceptive knowledge of eye position. *Vision Res*, *27*(10), 1737-1744.
- Stricanne, B., Andersen, R. A., & Mazzoni, P. (1996). Eye-centered, head-centered, and intermediate coding of remembered sound locations in area LIP. *J Neurophysiol*, *76*(3), 2071-2076.
- Swisher, J. D., Halko, M. A., Merabet, L. B., McMains, S. A., & Somers, D. C. (2007). Visual topography of human intraparietal sulcus. *J Neurosci*, *27*(20), 5326-5337. doi:10.1523/JNEUROSCI.0991-07.2007
- Thompson, A. A., & Henriques, D. Y. (2010). Locations of serial reach targets are coded in multiple reference frames. *Vision Res*, *50*(24), 2651-2660. doi:10.1016/j.visres.2010.09.013
- Treue, S., & Maunsell, J. H. (1996). Attentional modulation of visual motion processing in cortical areas MT and MST. *Nature*, *382*(6591), 539-541. doi:10.1038/382539a0
- van Beers, R. J., Sittig, A. C., & Gon, J. J. (1999). Integration of proprioceptive and visual position-information: An experimentally supported model. *J Neurophysiol*, *81*(3), 1355-1364.
- Van Pelt, S., Toni, I., Diedrichsen, J., & Medendorp, W. P. (2010). Repetition suppression dissociates spatial frames of reference in human saccade generation. *J Neurophysiol*, *104*(3), 1239-1248. doi:10.1152/jn.00393.2010
- Velliste, M., Perel, S., Spalding, M. C., Whitford, A. S., & Schwartz, A. B. (2008). Cortical control of a prosthetic arm for self-feeding. *Nature*, *453*(7198), 1098-1101. doi:10.1038/nature06996
- Wauschkuhn, B., Verleger, R., Wascher, E., Klostermann, W., Burk, M., Heide, W., & Kompf, D. (1998). Lateralized human cortical activity for shifting visuospatial attention and initiating saccades. *J Neurophysiol*, *80*(6), 2900-2910.
- Welvaert, M., & Rosseel, Y. (2013). On the definition of signal-to-noise ratio and contrast-to-noise ratio for fMRI data. *PLoS One*, *8*(11), e77089. doi:10.1371/journal.pone.0077089
- Whitehouse, A. J., & Bishop, D. V. (2009). Hemispheric division of function is the result of independent probabilistic biases. *Neuropsychologia*, *47*(8-9), 1938-1943. doi:10.1016/j.neuropsychologia.2009.03.005
- Wurtz, R. H. (2008). Neuronal mechanisms of visual stability. *Vision Res*, *48*(20), 2070-2089. doi:10.1016/j.visres.2008.03.021
- Xing, J., & Andersen, R. A. (2000). Models of the posterior parietal cortex which perform multimodal integration and represent space in several coordinate frames. *J Cogn Neurosci*, *12*(4), 601-614.
- Yeshurun, Y., & Carrasco, M. (1999). Spatial attention improves performance in spatial resolution tasks. *Vision Res*, *39*(2), 293-306.
- Zipser, D., & Andersen, R. A. (1988). A back-propagation programmed network that simulates response properties of a subset of posterior parietal neurons. *Nature*, *331*(6158), 679-684. doi:10.1038/331679a0

