ACTION INTENTION MODULATES THE ACTIVITY PATTERN IN EARLY VISUAL AREAS

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ABSTRACT

The activity pattern in the early visual cortex (EVC) can be used to predict upcoming actions as it is functionally connected to higher-order motor areas. However, the mechanism by which the EVC enhances action-relevant features is unclear. We explored this using fMRI. Participants performed Align or Open Hand movements to two oriented objects. We localized the calcarine sulcus, corresponding to the periphery, and the occipital pole, corresponding to the fovea. During planning, univariate analysis did not reveal significant results so we used multi-voxel pattern analysis (MVPA) to decode action type and object orientation. Though objects were located in the periphery, we found a significant decoding accuracy for orientation in an action-dependent manner in the occipital pole and action network areas. We established the functional connectivity between the EVC and somatomotor areas during planning using psychophysiological interaction (PPI) analysis. Taken together, our results show object orientation is modulated by action preparation.

DEDICATION

To Nala.

Thank you for your support and unconditional love.

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CHAPTER 1

GENERAL INTRODUCTION

1.0 Introduction

In daily life, there is a constant interaction between what we do and what we see. Extensive research has investigated visually guided actions, identifying numerous cortical areas required for action execution. These studies implicate separate frontoparietal networks for reaching and grasping (Andersen & Buneo, 2002; Culham, Cavina-Pratesi, & Singhal, 2006; Vesia & Crawford, 2012). However, performing an action requires the collective interaction of motor and visual brain areas. Though our actions are partly dictated by what we perceive, the reverse also holds, perception is modulated by action. Motor areas must provide feedback to the early visual cortex (EVC), which is essential for enhancing feature properties such as orientation. This feedback allows our perception to focus on key object features, which enable us to execute an action successfully (Gutteling et al., 2013; Gutteling et al., 2015; van Elk, van Schie, Neggers, Bekkering, & Sakata, 2010). Though feedforward connections have been studied extensively, only recently have researchers began to study how action modulates perception. Therefore, much is still unclear about the communication that goes back from the action network to early visual areas. Here, I describe that during action planning, object orientation can be decoded in an action-dependent way due to connectivity between higher-level cortical areas and the EVC.

1.1 Psychophysics of Orientation Processing

To interact with the world around us, we must have information about the location, shape, size and orientation of an object. Objects contain low-level feature information such as orientation, curvature and color as well as high-level features such as facial expression (Treisman & Gelade, 1980). Here, I will focus specifically on the low-level feature of orientation.

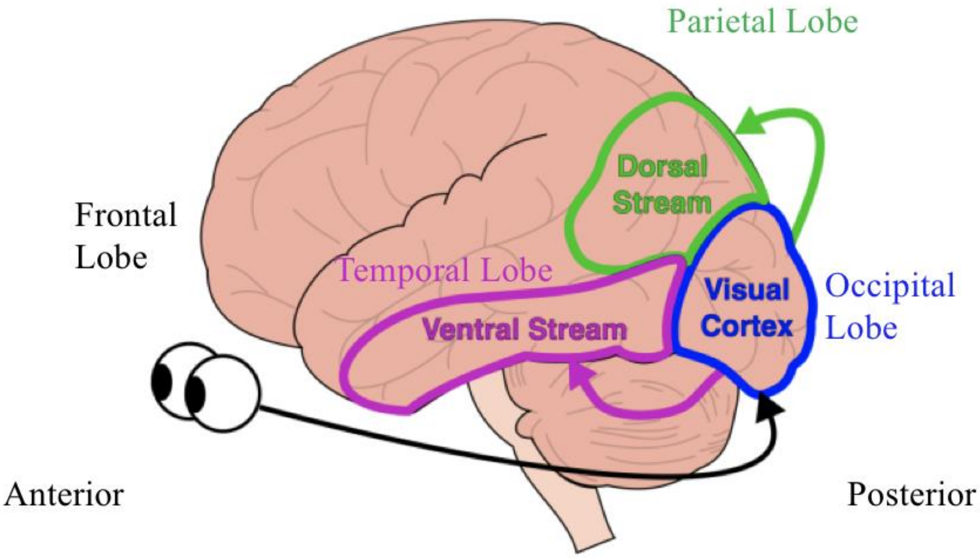
Hubel and Wiesel (1962) conducted experiments in the cat striate cortex and found that regions selectively respond to lines at particular orientations. Andrews (1967) showed that in humans, certain features such as object orientation are processed more efficiently than others due to orientation-selective cortical regions. Another study examined the ability of participants to discriminate line orientations from the vertical (Westheimer, Shimamura, & McKee, 1976). These authors found that participants could successfully discriminate orientation, even 0.3° away from the vertical. Additionally, with the presence of more line flankers, it was more difficult for participants to discriminate line orientation, due to the distraction (Westheimer et al., 1976). Carrasco and McElree (2001) asked participants to complete a feature and conjunction task. In the feature task, a grating at a particular orientation was presented among distractors. Participants had to indicate if the grating was shifted to the left or the right. Then, in the conjunction task, oriented gratings were presented among distractors but spatial frequency was also varied. These authors showed that orientation discrimination improved and so did the time required to process this information (Carrasco & McElree, 2001). Next, I will describe how this information from the environment is processed in the brain.

1.1a Cortical Areas that Process Orientation Information

Orientation information is processed in the occipital cortex. First, visual information enters the retina in the eye and gets transmitted to the simple cells of the lateral geniculate nucleus (LGN). This orientation information is then processed in early visual areas such as the striate cortex (Hubel & Wiesel, 1962, 1968). The striate cortex is topographically organized based on retinal stimulation. Like the center surround receptive fields of the retina and LGN, striate cortex neurons have excitatory and inhibitory areas. These areas are arranged side-by-side, in columnar form. Each column responds to a particular orientation and adjacent columns have slightly different orientation preferences. The sequence of orientation preferences gradually shifts. A similar organization was found in macaques and humans. De Valois, Albrecht, and Thorell (1982) showed that macaque neurons were more sensitive to both vertical and horizontal orientations. Moreover, they found a difference in the response of cells in the foveal versus parafoveal region (De Valois et al., 1982). Therefore, orientation information goes from the retina to the LGN and is processed by the EVC.

Object features such as orientation guide the brain in creating a plan enabling us to accurately reach for and grasp an object. Once information is processed in the occipital cortex, depending on the goal, it goes through one of two processing pathways as shown in Figure 1A. Ungerleider and Mishkin (1982) proposed the existence of two processing streams: an occipitotemporal and an occipitoparietal stream. This influential model of perception and action suggests that the occipitotemporal stream processes vision for perception and it is commonly known as the ventral stream (Goodale, & Milner, 1992). Vision for action relies on the occipitoparietal stream, commonly known as the dorsal stream (Carey, Dijkerman, Murphy, Goodale, & Milner, 2006; Goodale & Milner, 1992; Milner & Goodale, 2008). These two visual streams operate on different time scales. The ventral stream represents delayed actions as it requires information stored over a longer time scale than immediate actions which are processed by the dorsal stream, involved in continuous, real-time changes to motor planning (Goodale, Jakobson, Keilor, & 1994; Goodale, Westwood, & Milner, 2004). However, these two streams do work in conjunction with one another for a motor command to be executed (Valyear, Culham, Sharif, Westwood, & Goodale, 2006).

A. Feedforward Connections



B. Feedback Connections

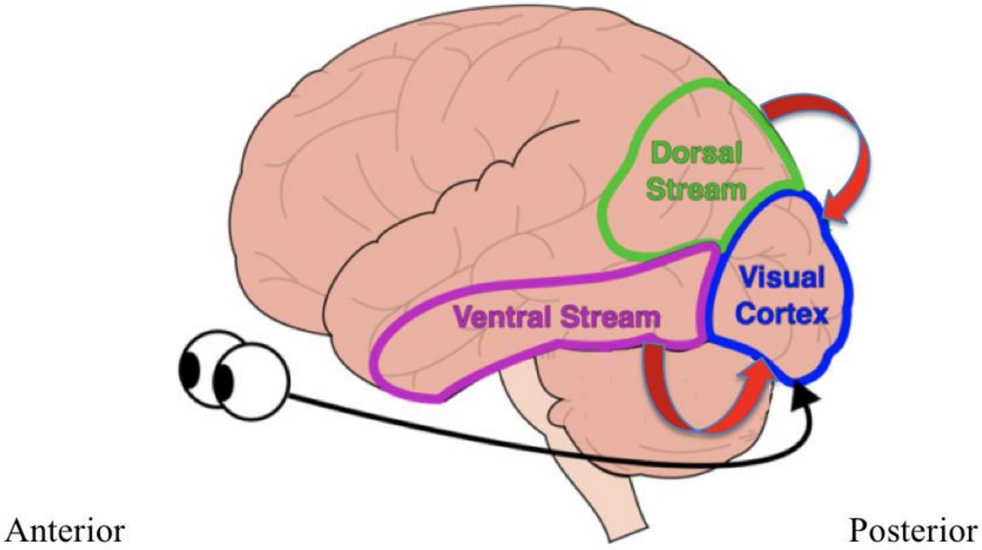


Figure 1.
Schematic of feedforward (A) and feedback connections (B) between the visual and the parietal cortex (dorsal stream) as well as the visual and temporal cortex (ventral stream).

Studies investigating motor preparation have focused on shifts of spatial attention to target location. However, effects of visual attention on the processing of orientation, a non-spatial stimulus feature, has been reported for both early event-related potential (ERP) components and slow-wave ERP effects (Baas, Kenemans, & Mangun, 2002; Eimer, Van Velzen, Gherri, & Press, 2006; Slagter, Kok, Mol, & Kenemans, 2005). For example, an increased amplitude of N1 and P1 components were found when participants attended to object orientation, suggesting that early visual brain responses are enhanced when attending to non-spatial stimulus features. Moreover, Harrison and Tong (2009) found that when participants had to remember the precise orientation of an object, this orientation tuning was strongest in the primary visual cortex (V1). This orientation-selective pattern was exhibited with a mean accuracy level upwards of 80%. Since orientation is a relevant feature for grasping, perceptual enhancement of action-relevant features during motor preparation occurred. Indeed, when participants performed an orientation change detection task while preparing a grasp or point towards an object, orientation change perception improved significantly for the grasp but not the point (Gutteling, Kenemans, & Neggers, 2011). Since the EVC processes orientation and this information is essential for action execution, we examined this object property in our study.

1.2 Reach and Grasp Kinematics

Our interaction with objects seems effortless; however, the kinematics and kinetics of reaching and grasping require multiple joint rotations, hand rotations and muscle activation. Though there are multiple paths between two points, there are constraints that control hand movement. For example, the limb end-point trajectory follows a straight path (Morasso, 1981), illustrating that arm movements are planned in extrinsic coordinates (Hogan & Flash, 1987). While this is the dominant model, Desmurget, Jordan, Prablanc, and Jeannerod (1997) suggest that intrinsic coordinates involving muscle activation and joint rotation are responsible for motor plans. What both models have in common is optimization principles that produce smooth movements that are also accurate, minimizing the number of joints required and preserving final posture (Desmurget et al., 1997).

Velocity profiles have been used to study reaching and grasping. When making a movement, acceleration occurs until a peak of 50% is reached after which deceleration occurs until contact between the target and effector is made (Bennett & Castiello, 1994). This transport velocity curve is bell-shaped and symmetrical, where both acceleration and deceleration phases are equal. Due to this, jerk is minimized, providing optimal movement control (Jeannerod, 1999). Moreover, when grasping an object, the distance between the thumb and index finger increases until 70% of the movement is made at which the grip aperture decreases until the hand makes contact with the object (Jeannerod, 1984). During the deceleration phase, several corrective movements are made due to sensory feedback (Jennerod 1984). Changing the size of the object and its shape effects maximum grip aperture, however the time to reach the maximum remains the same (Gentilucci et al., 1991).

Jeannerod (1984) suggested that reaching and grasping occur through two separate, parallel channels. Reaching is centered on the target in space, while grasping involves direct interaction with the object. In particular, reaching requires computations of the distance from the object in egocentric frames of reference and engages proximal joints and muscles, while grasping relies on intrinsic object properties such as shape and size (Jeannerod, 1999). Next, I describe the cortical areas that coordinate the planning and control of goal-directed actions.

1.2a Cortical Areas of Reaching and Grasping

Considerable research has investigated the neural substrates implicated in performing actions. Action planning requires the interaction of multiple cortical areas. The classical model of action planning involves areas located in the posteromedial IPS for planning reaches, while the anterolateral IPS contributes to planning grasps (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995). Non-human primate neurophysiology, fMRI and patient studies have confirmed distinct modules of activation in the posterior parietal cortex (PPC). Reaching involves areas V6A (SPOC in humans), the medial intraparietal (MIP) area (mIPS in humans) and the dorsal premotor cortex (PMd) (Cavina-Pratesi et al., 2010; DeSouza et al., 2000; Fernandez-Ruiz, Goltz, DeSouza, Vilis, & Crawford, 2007; Filimon, Nelson, Huang, & Sereno, 2009; Króliczak, McAdam, Quinlan, & Culham, 2008; Medendorp, Tweed, & Crawford, 2003; Tosoni, Galati, Romani, & Corbetta, 2008). In contrast, the grasping circuit requires the anterior intraparietal (AIP) region (aIPS in humans) and the ventral premotor cortex (PMv), specifically the rostral portion (PMvr) (Fagg & Arbib, 1998; Murata et al., 2014).

1.2a. i The Posterior Parietal Cortex (PPC)

The PPC is a high-level cognitive area subserving functions related to action execution and visuomotor function (Andersen & Buneo, 2002; Culham et al., 2006; Iacoboni, 2006; Rizzolatti, Fogassi, & Gallese, 1997). Our initial understanding of PPC function comes from neurophysiological studies in the monkey, highlighting the role of the PPC in preparing actions involving the arm, hand and eye. Neuroimaging studies in humans have identified homologs to macaque PPC areas. Here, I will describe how information goes from key PPC reach areas (SPOC and mIPS) and grasp areas (aIPS) to the premotor cortex for movement execution as shown in Figure 2.

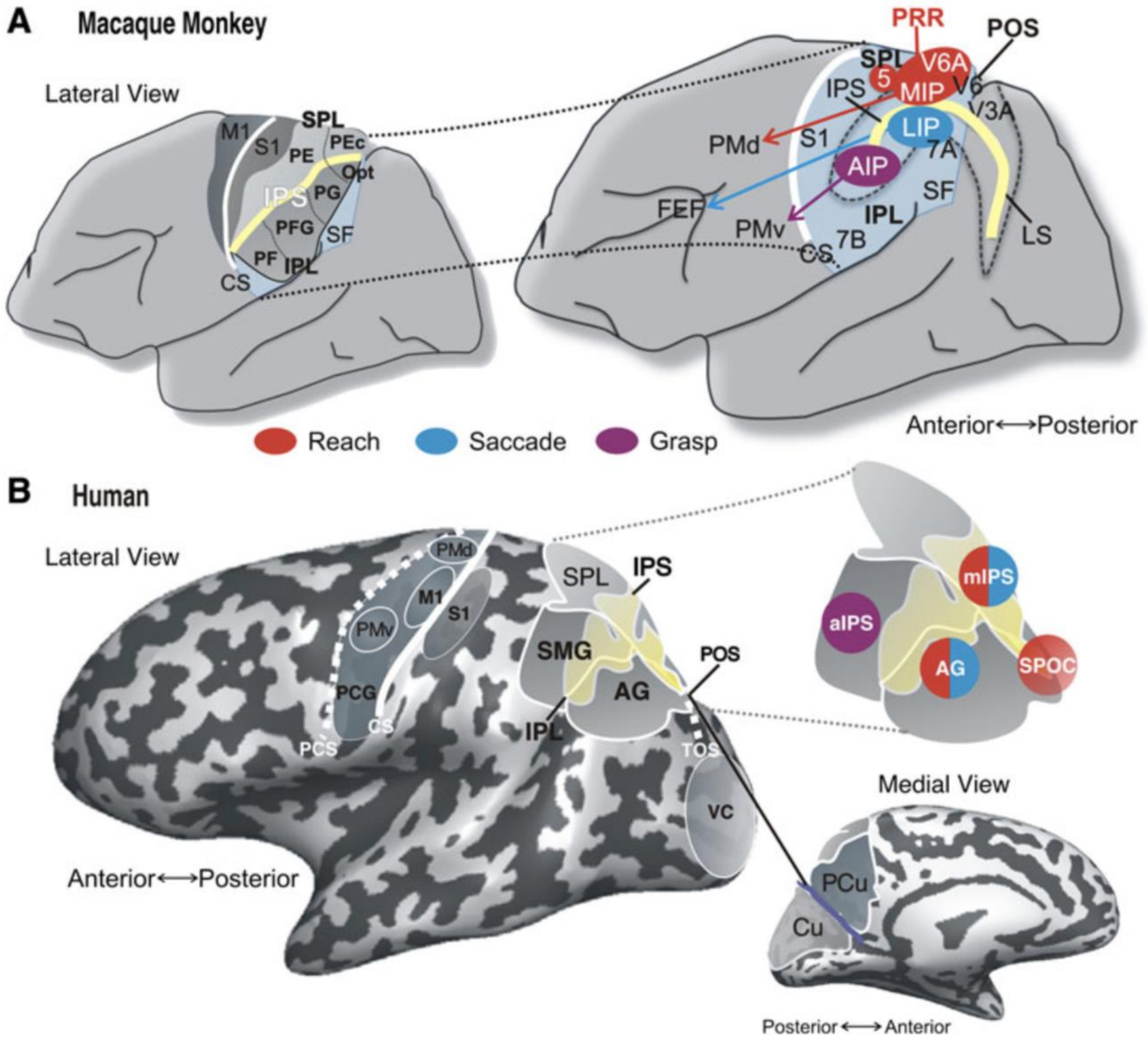


Figure 2.
Comparison of macaque (A) and human brain (B) showing the basic anatomy of the visuomotor function in the posterior parietal cortex for saccade, reach and grasp. In the macaque monkey brain (A) the intraparietal sulcus (IPS) and lunate sulcus (LS) of monkey brain in rightmost panel have been opened up to reveal the fundus and banks of each sulcus. (B) Human brain neuroanatomy differs substantially from that of monkey. *CS* central sulcus, *SF* sylvian fissure, *POS* parieto-occipital sulcus, *TOS* transverse occipital sulcus, *PCS* post-central sulcus, *SPL* superior parietal lobule (PE, PEc), *IPL* inferior parietal lobule (Opt, PG, PFG, PF), *S1* primary somatosensory cortex, *M1* primary motor cortex, *Brodmann's areas 5* 7A and 7B, *visual areas V3A* V6A, *AIP anterior, MIP* medial, *LIP* lateral sections of IPS, *VC* visual cortex, *AG* angular gyrus, *aIPS* anterior part of IPS, *mIPS* midposterior part of IPS, *SPOC* superior parieto-occipital cortex, *PMd* dorsal premotor cortex, *PMv* ventral dorsal premotor cortex, *FEF* frontal eye fields, *SMG* supramarginal gyrus, *PCG* postcentral gyrus, *PCu* precuneus, *Cu* cuneus (This figure and caption was taken from Vesia and Crawford, 2012).

In particular, V6A or SPOC in humans, has been found to code wrist orientation (Cavina-Pratesi et al., 2010; Filimon, 2010; Monaco et al., 2011). Lesions to macaque PPC (Faugier-Grimaud, Frenois, & Peronnet, 1985; Faugier-Grimaud, Frenois, & Stein, 1978), and specifically to V6A (Battaglini et al., 2002), resulted in awkward hand and wrist postures when grasping objects. V6A has been shown to be modulated by the direction of arm movements to visual or remembered targets (Fattori, Gamberini, Kutz, & Galletti, 2001) and the arm and hand position in space (Galletti, Fattori, Kutz, & Battaglini, 1997; Fattori et al., 2010). Moreover, lesions to SPOC not only lead to reaching errors (Jakobson, Archibald, Carey, & Goodale, 1991; Jeannerod, 1986), but also to difficulties in achieving an appropriate wrist posture (Karnath & Perenin, 2005; Karnath & Rorden, 2012). Furthermore, when Vesia, Prime, Yan, Sergio, and Crawford (2010) used online, event related rTMS, stimulation of SPOC caused a deviation in reach end points. Therefore, SPOC has been implicated in wrist posture, specifically in the control of overall hand orientation.

Macaque MIP has been implicated in selective hand direction and stimulus direction. Damage to this area resulted in reaching errors (Eskandar & Assad, 1999). Its homolog, mIPS encodes both pointing and reaching preparation (Beurze, de Lange, Toni, & Medendorp, 2009; DeSouza et al., 2000; Fernandez-Ruiz et al., 2007; Grefkes, Ritzl, Zilles, & Fink, 2004; Medendorp, Goltz, Crawford, & Vilis, 2005; Medendorp, Goltz, Vilis, & Crawford, 2003).

The AIP has been modulated by the shape, size, orientation and configuration of a graspable object (Taira, Mine, Georgopoulos, Murata, & Sakata, 1990; Vesia & Crawford, 2012). In humans, the aIPS is highly involved in the preshaping of the fingers and has been found to be maximally active to grasp, as compared to any other movement (Cavina-Pratesi et al., 2010; Culham et al., 2003; Monaco, Gallivan, Figley, Singhal, & Culham, 2017). During action execution, this area orients the wrist (Baumann, Fluet, & Scherberger, 2009; Murata, Gallese, Luppino, Kaseda, & Sakata, 2000). TMS studies in humans have found that stimulation to aIPS disrupts corrections to changes in wrist orientation, especially when administered early in processing (Tunik, Frey, & Grafton, 2005).

Multisensory information from the PPC goes to the premotor cortex which plays a role in movement preparation and execution (Crammond & Kalaska, 2000). The premotor cortex is divided into sub-regions including the dorsal premotor cortex (PMd) and ventral premotor cortex (PMv). The PMd is involved in the planning of movements as it determines movement direction and trajectory, not final limb position in space (Caminiti, Johnson, Galli, Ferraina, & Burnod, 1991). It encodes transport and grip components of grasping movements (Cavina-Pratesi et al., 2010; Monaco et al., 2011). While PMd is more involved in proximal components such as power-grip and reach-related movements, PMv is responsible for distal components such as hand preshaping and grip-specific responses. Neuronal activity in the PMv is related to grip type: different groups of neurons were active during precision grips, during finger prehension (grasping) or during whole hand prehension (Davare et al., 2006; Murata et al., 2014; Rizzolatti et al., 1988).

1.3 Motor Feedback to Visual Areas

Not only is the PPC required for the transformation of visual information into a motor plan (Crawford, Henriques, & Medendorp, 2011), but also in feeding back information to guide movement execution as shown in Figure 1B (Iacoboni, 2006). When planning an action, relevant object features such as orientation and location must be obtained and examined with maximum possible accuracy before initiating an action. Enhanced perception is thus triggered by the mere intention to grasp. Several behavioral studies have shown evidence for an “action-modulated perception,” a mechanism that automatically enhances relevant features during the planning phase for an action (Bekkering & Neggers, 2002; Craighero, Fadiga, Rizzolatti, & Umiltà, 1999; Fagioli, Hommel, & Schubotz, 2007; Hannus, Cornelissen, Lindemann, & Bekkering, 2005).

1.3a Behavioral Studies

Visual search studies showed that the intention to act resulted in the selection of action-relevant information (Bekkering & Neggers, 2002; Craighero et al., 1999; Hannus et al., 2005). For instance, Bekkering and Neggers (2002) instructed participants to either grasp or point to a target that was defined by a specific orientation and color. Fewer saccades to objects with the wrong orientation were made when participants performed grasping compared to pointing. However, saccades to objects with the wrong color were the same, regardless of the action to be performed. This suggests that the intention to grasp causes the enhancement of action-relevant features. Additionally, early visual brain responses were enhanced when probes were presented at the location of an intended movement (Baldauf & Deubel, 2009) and when stimuli appeared at covertly attended locations (Hillyard & Anllo-Vento, 1998). This could be due to feedback from the frontoparietal network, activated during response preparation (Praamstra, Boutsen, & Humphreys, 2005).

Using behavioral methods, van Elk and colleagues (2010) first showed that action preparation might drive perceptual changes in the visual cortex through feedback connections. Participants either grasped or pointed to a three-dimensional target object while ERPs were recorded relative to stimulus onset. They found evidence for occipital activity modulation shortly before participants grasped. Moreover, when comparing grasping to pointing, there was a stronger N1 component and a subsequent selection negativity, which was localized to the lateral occipital complex. This suggests that the intention to grasp influences the processing of action-relevant features such as object orientation in ventral stream areas already at an early stage. However, behavioral studies do not allow us to examine the neural mechanisms that induce modulation.

1.3b Neuroimaging Studies

Neuroimaging studies have shown that the enhancement of action-relevant features relies on brain areas including the EVC as well as the dorsal and ventral stream. An fMRI study that measured brain activation during delayed reaching and grasping found that the EVC and the lateral occipital cortex (LOC), a ventral stream area implicated in multimodal object recognition were active (Singhal, Monaco, Kaufman, & Culham, 2013). This reactivation was observed even though participants remained in complete darkness with no visual stimulation at the time of the action. These areas were active in addition to areas expected in action execution, such as the primary motor cortex (M1) and the supplementary motor area (SMA). This suggests that motor areas plan actions and for these actions to be carried out, visual information must be re-recruited. However, the details of how visual areas are re-recruited remains unclear.

Gutteling and colleagues (2013) showed that perception is enhanced when planning to grasp due to top-down feedback to early visual areas. By applying TMS to aIPS, a grasping motor area, orientation sensitivity was modulated for grasping as compared to pointing preparation. Since orientation is a key feature for grasping but not pointing, this shows that action-relevant features are selectively modulated based on the movement to be performed. This work was taken a step further through the use of high-resolution fMRI and multivariate techniques. In a study by Gutteling and colleagues (2015), participants planned then executed an action (go condition) or only planned actions (no-go condition). With MVPA, these authors decoded with >70% accuracy whether a grasping or pointing action was prepared from EVC signals. Even in no-go trials, classification was still above chance level, demonstrating that actual action performance has little effect on the EVC.

A recent fMRI study separated spatial target representation, motor planning and execution to differentiate the cortical areas involved in each phase (Cappadocia, Monaco, Chen, Blohm, & Crawford, 2017). The authors confirmed the findings of previous studies which showed that during planning, the classic frontoparietal network was active, including areas such as SPOC, mIPS, SMA, PMd and M1 (Gallivan & Culham, 2015). Also, they observed occipital reactivation, linking several areas in the occipital cortex to action planning. In particular, during planning, areas such as the lingual gyrus (LG), inferior occipital gyrus (IOG) and superior occipital gyrus (OG) were active (Cappadocia et al., 2017). This means that occipital areas are not only active during actual action execution (Chen et al., 2014) but also during planning. This further demonstrates that visual areas are active when planning an action.

These studies show that when planning an action, dorsal and ventral stream areas are active. Interestingly, they illustrate the activation of visual areas as well. However, comparing a grasping action to a pointing action only allows us to speculate what brain areas are responsible for action preparation. It is important to study two types of grasping actions to determine if the same brain regions are recruited when an object is presented at different orientations and to directly compare the neural substrates involved in performing actions. Thus, much is still unclear about the pathway of communication between motor planning areas and early visual areas.

1.3c Connectivity Studies

Two studies have used functional connectivity to illustrate how perception is modulated by higher order areas. A study by Tal, Geva, and Amedi (2016) explored visual cortex activation in response to touch and how the coupling between the parietal and visual cortices is manifested. With PPI, they found that LOC was activated by touch as it is functionally connected to the primary somatosensory cortex (S1). Additionally, Monaco and colleagues (2017) investigated tactile and visual exploration during delayed actions. Using PPI, they showed a stronger functional connectivity between the occipital pole (corresponding to foveal vision), aIPS and LOC. However, both these studies examined connectivity during action execution, the time at which haptic exploration of objects occurred, not during action planning.

1.4 Neuroimaging

Since my study used fMRI to determine connectivity between EVC and somatomotor areas during planning, I will describe the technique here. Then I will describe MVPA and PPI.

1.4a Functional Magnetic Resonance Imaging (fMRI)

Since we cannot measure neuronal activity directly, fMRI utilizes blood-oxygen-level dependent (BOLD) signals to indirectly measure activity levels in the brain as participants perform particular tasks. The BOLD signal is used to study local changes in deoxyhemoglobin concentration in the brain (Ogawa et al., 1992). The information provided by the BOLD signal allows us to make conclusions about the underlying neuronal activation. If a brain region displays a higher BOLD signal, it means that it is more involved in a particular task. By participants engaging in an experiment with different movements, we can determine the brain areas that are responsible for each movement. The signal changes during a task can be described by the hemodynamic response function (HRF), where peak activation is 4-6 seconds after activation (Friston, Frith, Frackowiak, & Turner, 1995). Accurately modeling the HRF to a neural event is essential for fMRI analysis. BOLD signals can be modeled by the general linear model (GLM) to make statistical inferences at every voxel using univariate tests. fMRI allows us to measure changing stimulus or task conditions with a high spatial and temporal resolution.

For fMRI studies, there are two major types of experimental designs: block and event-related designs. In block designs, a condition is presented continuously, for an extended period and different conditions are presented in separate blocks. These designs are robust (Brockway, 2000; Rombouts et al., 1997), display a large BOLD signal relative to baseline (Buxton, Wong, & Frank, 1998) and have increased statistical power (Friston, Holmes, Price, Büchel, & Worsley, 1999). In an event-related design, short, discrete events are presented with an order and timing that can be randomized, allowing for transient variations in the hemodynamic response to be detected, analysis of individual trials (Schacter, Buckner, Koutstaal, Dale, & Rosen, 1997) and reduced participant expectation effects (D’Esposito, Zarahn, & Aguirre, 1999). Event-related designs can be fast, where the intertrial interval (ITI) is shorter than the duration of the HRF (Buckner et al., 1998), or slow, where the ITI is longer in duration than the HRF, typically 10-12 seconds (Buckner et al., 1996). We used a slow event-related design as it allowed us to focus our analysis on the planning phase which was between the auditory cue indicating the action to be completed at the end of the trial and action execution.

1.4b Multi-Voxel Pattern Analysis (MVPA)

Traditionally, fMRI analyses characterized the relationship between cognitive states and individual voxels. A statistically significant response was shown during experimental conditions by spatially averaging across significant voxels. However, this eliminates voxels which may carry useful information and blurs fine-grained spatial patterns (Kriegeskorte, Goebel, & Bandettini, 2006). Examining voxels in isolation may not be a sensitive enough technique and it does not allow us to characterize functional relationships between brain regions. Instead of focusing on individual voxels, MVPA uses pattern classification algorithms to decode the information that is represented in that pattern of activity, even if individually each voxel might not show a significant response. In addition to allowing us to sensitively detect and track cognitive states, MVPA allows us to characterize representation: what information is represented in different brain areas, how it is represented and how it is transformed at different processing stages (Norman, Polyn, Detre, & Haxby, 2006).

MVPA is a pattern classification technique. After participants view stimuli from two object categories, feature selection is used to determine which voxels will be included in the classification analysis. Pattern assembly sorts the data into discrete brain patterns. This corresponds to the selected voxels pattern of activity at a particular time. The patterns are labeled according to the experimental condition that generated it. Next, classifier training involves putting a subset of the labeled data through a multivariate pattern classification algorithm. This allows for the mapping between voxel activity patterns and experimental conditions. Lastly, during generalization testing a trained classifier is presented with a new pattern of brain activity to determine if it can correctly associate that pattern with the experimental condition. For more details about the methodology refer to Norman et al. (2006). Figure 3 shows a hypothetical experiment and how MVPA can be used to analyze it.

Our present understanding of the neural mechanisms that govern the planning of movements predominantly come from invasive frontoparietal neural recordings in nonhuman primates. Previous fMRI studies that used univariate techniques to examine plan-related activity in frontoparietal networks have been met with mixed degrees of success. Especially with action planning, the conventional fMRI approach lacks the sensitivity to detect certain types of neural information as it compares response amplitudes and examines each voxel independently (Haxby et al., 2001; Kamitani & Tong, 2005; Kriegeskorte & Bandettini, 2007). For example, through the use of multivariate techniques, Gallivan and colleagues (2013) uncovered extensive action planning not only in the dorsal stream as one would expect, but also in the ventral stream. This suggests top-down signals guide the preparation of a movement, specifically aimed at perceiving object features such as orientation to optimally facilitate action execution. The use of signal decoding allows for the determination of the neural signals that underlie the planning and implementation of real object-directed hand actions in humans. Moreover, by examining the pattern of activation in voxels, we can determine the different roles played by areas implicated in action planning, advancing previous notions of contributions to movement (Filimon, 2010). Here, we were motivated to use multivariate techniques such as MVPA as conventional univariate techniques were not sensitive enough for us to detect how two orientations were decoded better in Align versus Open Hand movements during planning.

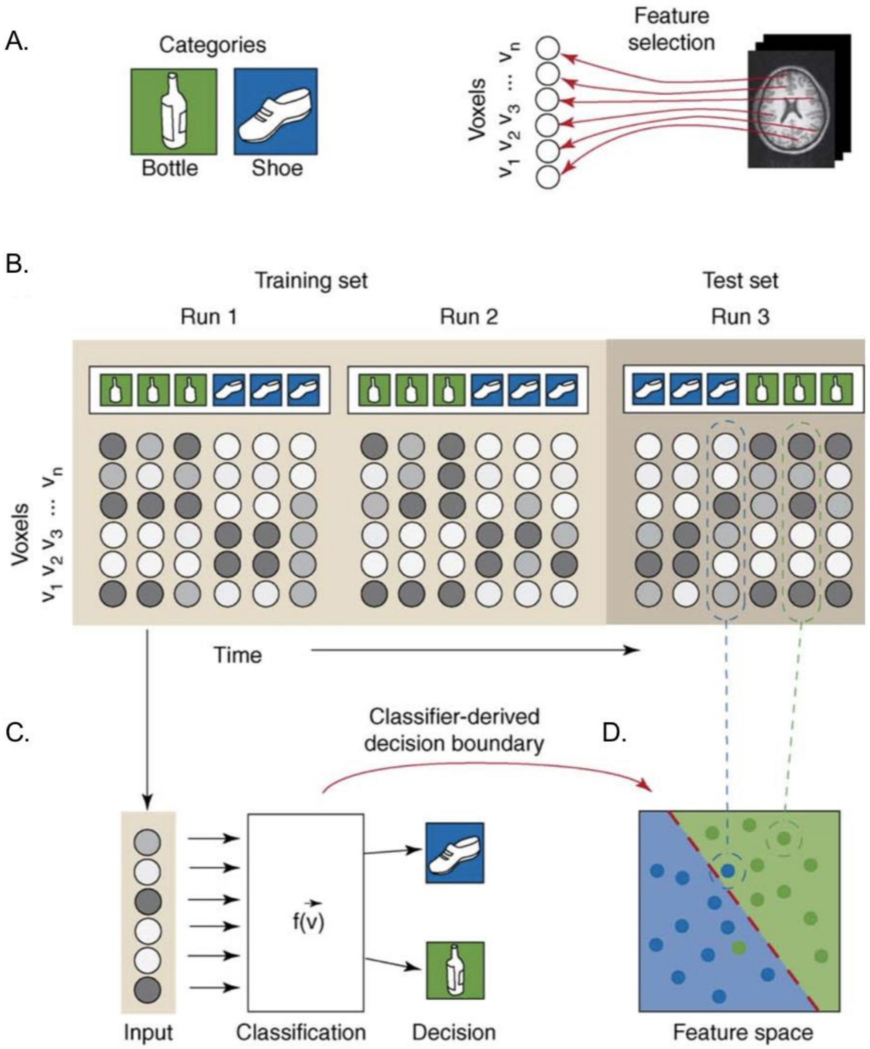


Figure 3.
Illustration of a hypothetical experiment and how it could be analyzed using MVPA. (A) Subjects view stimuli from two object categories (bottles and shoes). A ‘feature selection’ procedure is used to determine which voxels will be included in the classification analysis. (B) The fMRI time series is decomposed into discrete brain patterns that correspond to the pattern of activity across the selected voxels at a particular point in time. Each brain pattern is labeled according to the corresponding experimental condition (bottle versus shoe). The patterns are divided into a training set and a testing set. (C) Patterns from the training set are used to train a classifier function that maps between brain patterns and experimental conditions. (D) The trained classifier function defines a decision boundary (red dashed line, right) in the high-dimensional space of voxel patterns (collapsed here to 2-D for illustrative purposes). Each dot corresponds to a pattern and the color of the dot indicates its category. The background color of the figure corresponds to the guess the classifier makes for patterns in that region. The trained classifier is used to predict category membership for patterns from the test set. The figure shows one example of the classifier correctly identifying a bottle pattern (green dot) as a bottle, and one example of the classifier misidentifying a shoe pattern (blue dot) as a bottle. (The figure and caption was taken from Norman et al., 2006).

1.4c Psychophysiological Interaction (PPI) Analysis

Functional connectivity analyses such as PPI allows researchers to determine which voxels increase their relationship with a seed region of interest in a particular context (O'Reilly, Woolrich, Behrens, Smith, & Johansen-Berg, 2012). This way, researchers not only identify the activity in individual brain areas, but determine how information flows between areas (Friston, 2011). They can also determine how areas change their connectivity to participate in different networks under different times and circumstances (Cacioppo & Decety, 2011). In particular, with PPI, we investigated task-specific changes in different brain areas.

PPI identifies regions whose activity depends on the interaction between the task (psychological component) and the time course of the region of interest (physiological component) as shown in Figure 4 (Friston et al., 1997). PPI accounts for confounds that can change the relationship between brain areas. For example, the anatomical connections of areas with the seed region would have a positive relationship, correlating with the seed regardless of the task. Importantly, PPI does not give us information about causality. There is no implication that the seed region is a driver rather than the driven area (O'Reilly et al., 2012). While MVPA allowed us to decode orientation in different actions in EVC as well as dorsal and ventral stream areas, PPI allowed us to examine the connectivity between these areas in a task-specific way.

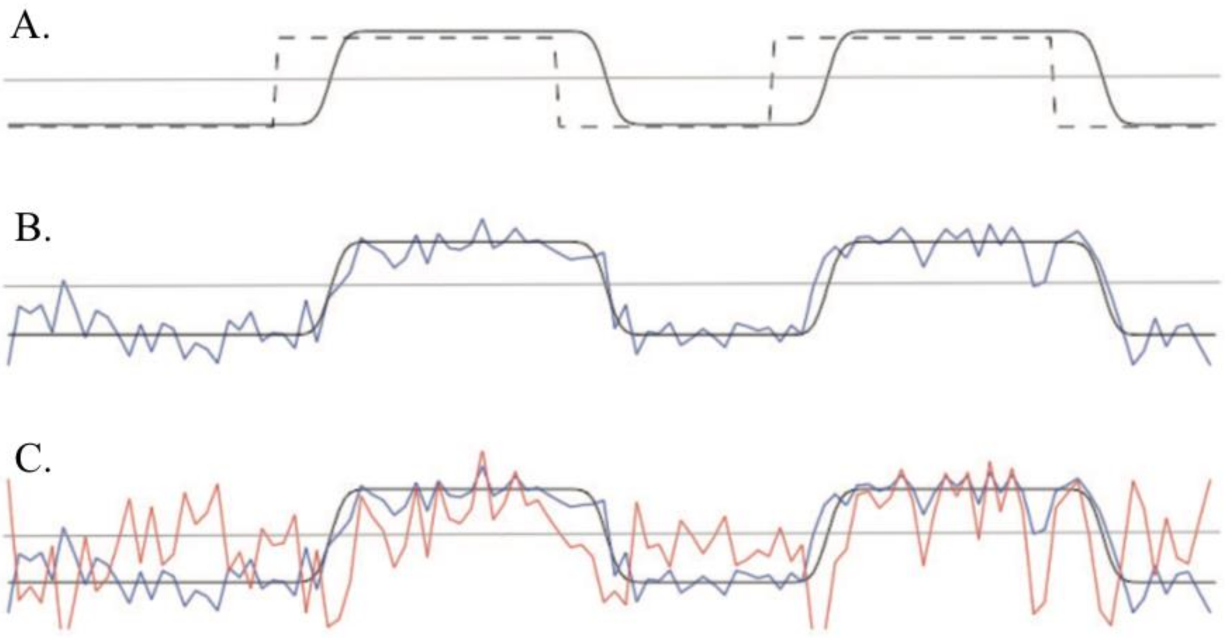


Figure 4.
Generating a PPI regressor. (A) We start with a regressor representing the main effect of task (in this case, a block design) (dashed line), and convolve it with the HRF to get an HRF convolved task regressor (black line). The horizontal grey line is zero. (B) We extract a time course from our seed region of interest (blue line). If this region of interest was active during the task, the time course of activity from the seed region will be correlated with the HRF convolved task regressor. (C) We generate a PPI regressor (red line) as an element-by-element product of the HRF convolved task (black line) and seed ROI (blue line) regressors. Note that the PPI regressor is correlated with the seed region time course during task blocks, but anti-correlated with it during rest blocks. Consequently, voxels that are always correlated with the seed ROI (e.g. due to anatomical connections that are not task-relevant) will have an overall regression co-efficient of zero for the PPI regressor, but voxels which are more correlated with the seed ROI during task blocks than during rest will show a positive correlation with the PPI regressor. (This figure and caption are from O'Reilly et al., 2006).

1.5 Specific Questions and Hypothesis

While the frontoparietal network for reaching and grasping has been extensively studied, little is known about feedback connections from motor areas to EVC during action preparation. Behavioral studies have shown that the perception of features such as orientation can be modulated by actions. fMRI has demonstrated that visual areas are re-recruited for movements to be executed, possibly due to top-down connections from the dorsal and ventral stream. Connectivity studies have illustrated that visual and higher order areas are functionally connected, however this was in the presence of tactile information, during action execution.

In the following chapter, I describe the study we completed to determine the neural mechanism of object feature enhancement during action planning. We had four questions that we explored. We wanted to determine if we could dissociate action intention. However, our main question asked if during planning, the activity pattern for object orientation is enhanced in an action-dependent manner. Next, based on these two questions, we asked what part of the visual field this decoding would be present in as objects were presented in the periphery, while participants gazed at the fixation point. Lastly, we asked if this decoding was due to a task-dependent functional connectivity between early visual areas and the rest of the brain. We conducted a slow event-related fMRI study to answer these questions. We hypothesized that action type and orientation can be dissociated due to connectivity between higher-level motor areas and the EVC and that this dissociation will only exist for the peripheral visual field as that is where objects were located. Since our univariate analysis did not reveal significant results, we examined the activity pattern for action type and object orientation in the EVC as well as the dorsal and ventral stream with MVPA and determined the connectivity amongst brain areas with

PPI. Therefore, we examined how perception is influenced by an action through MVPA and looked at the action itself using PPI.

In Chapter 3, I will describe how our findings contribute to movement planning and execution research. I will discuss future research avenues and questions that still remain from our study. Lastly, I will describe the practical applications of our findings.

CHAPTER 2

ACTION INTENTION MODULATES THE NEURAL CORRELATES UNDERLYING ORIENTATION PROCESSING

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A manuscript prepared to be submitted for publication.

2.0 Abstract

The role of the early visual cortex (EVC) has been extensively studied for visual recognition but to a lesser degree to determine how action planning influences perceptual representations of objects. We used a slow event-related fMRI paradigm to determine if during action planning, action type and object orientation could be decoded and if so, whether this was due to connectivity between visual and higher-level cortical areas. 16 participants used their dominant right hand to perform movements (Align or Open Hand) to two oriented objects placed on either side of a fixation cross. While Align movements required participants to adjust their hand precisely according to object orientation, Open Hand movements were coarse. Therefore, during action preparation, we hypothesized enhanced modulation of the activity pattern in the EVC for Align as compared to Open Hand tasks. We used eccentricity mapping to localize the peripheral cortex, corresponding to the retinotopic location of the objects in the EVC, and foveal cortex, corresponding to central vision. Since univariate contrasts did not reveal significant results during planning, we used multi-voxel pattern analysis (MVPA). During planning, an action-dependent dissociation was not significant; however, we found an above chance decoding accuracy of object orientation regardless of action type in the calcarine sulcus, corresponding to the location of the objects in peripheral vision. Strikingly, we found a significant decoding accuracy for Align but not Open Hand movements during planning in the occipital pole, corresponding to the foveal cortex, and dorsal stream areas such as SPOC and left pIPS. Additionally, psychophysiological interaction (PPI) analysis indicated a stronger functional connectivity between EVC and left M1/S1 as well as left SMA for Align versus Open Hand movements. These results demonstrate that action preparation modulates activity in early visual areas.

Keywords: action planning, early visual cortex, feedback connections, fMRI, multi-voxel pattern analysis (MVPA), psychophysiological interaction (PPI) analysis

2.1 Introduction

To execute actions in daily life successfully, our brain needs to obtain accurate information about the orientation, location, shape and size of a target object. Picking up a pen, for example, would be more successful when one is focused on its orientation rather than its color. Considerable research has investigated the role of frontoparietal reaching and grasping networks in successfully executing actions (Andersen & Buneo, 2002; Crawford, Henriques, & Medendorp, 2011; Culham et al., 2003; Vesia & Crawford, 2012; Westendorff, Klaes, & Gail, 2010). However, perception is enhanced by the mere intention to grasp. Recent fMRI (Harrison & Tong, 2009; Singhal, Monaco, Kaufman, & Culham, 2013), TMS (Mevorach, Humphreys, & Shalev, 2009; Silvanto, Muggleton, Lavie, & Walsh, 2009), and studies that used both techniques together (Mevorach, Hodsoll, Allen, Shalev, & Humphreys, 2010; Ruff et al., 2008) have shown evidence for "action-modulated perception," a top-down mechanism that enhances relevant features for a task. The outstanding question is whether object features become enhanced at the moment when an action is intended but not yet executed, and if this mechanism can be decoded from the activity pattern in the EVC.

Enhanced feature perception during action planning could be mediated by feedback connections between motor areas and the EVC. A study by van Elk and colleagues (2010) has shown evidence for preparatory activity in visual areas shortly before grasping. Additionally, fMRI studies have shown that the EVC is reactivated at the time of delayed actions despite the absence of visual information (Monaco et al., 2017; Singhal et al., 2013) and above baseline activation for reaching movements, even when actions were only prepared but not yet executed (Cappadocia et al., 2017; Gutteling et al., 2013; Gutteling et al., 2015). The re-recruitment of the EVC might enhance the processing of object feature information and digit placement to accurately plan an action.

The use of the above approach of comparing grasping to pointing allows us to investigate which brain areas are involved in action preparation. However, the mechanism by which the activity pattern for object orientation is enhanced by action planning remains unknown. The goals of this study were to determine: i) whether representation of object orientation is enhanced by plans for hand movement in EVC, ii) whether this depends on the details of the action, and iii) which functional connections between the EVC and reach-related brain areas might produce these modulations. Since univariate analysis failed to uncover influences of action preparation in early visual areas, we used MVPA and PPI. We hypothesized that during planning, an action-dependent dissociation (Figure 6B, left panel) and orientation processing (Figure 6B, right panel) in EVC is affected by higher-level areas, possibly as a consequence of feedback from motor areas, supporting subsequent visually guided action. Therefore, the activity pattern elicited by object orientation would be enhanced by the action that needs to be adjusted in a task-dependent manner.

2.2 Methods

We explored whether we could predict action intention within the left and right object location in visual areas and areas of the action network (Figure 6B, left panel). However, our main question (Figure 6B, right panel) was aimed to investigate whether the activity in the EVC elicited by oriented visual stimuli is modulated by action intention. To this aim, we examined the activity pattern in the calcarine sulcus, corresponding to the retinotopic location of the objects, as well as in other regions of interest in EVC and in the dorsal and ventral stream. If the representation of an object is shaped by the intended action, we would see enhanced dissociation between the two object orientations when participants were planning an action that had to be adjusted to the orientation of the object (Align) as compared to a movement for which object orientation was irrelevant (Open Hand).

2.2a Participants

Twenty-six right-handed volunteers, 14 females and 12 males (age range of 20-45, with an average age of 30.4 years) participated in this study. 16 participants took part in the experimental runs and 14 participants volunteered for the independent localizer runs for retinotopic mapping. 4 of these participants took part in both sessions. All participants had normal or corrected-to-normal vision and none of the participants had any known neurological deficits. All participants provided informed consent and approval was obtained from the ethics committee for experiments involving human participants at the University of Trento.

2.2b Experimental Setup (Apparatus and Stimuli)

The experimental setup is illustrated in Figure 5A. Participants lay on the bed of a 4-Tesla MRI scanner and performed actions towards two real objects. Both objects were affixed to strips of Velcro attached to a platform that was covered with the complementary side of Velcro. The platform was placed over the pelvis of the participant. This device enabled participants to perform hand actions (Align and Open Hand movements) towards two wooden objects mounted on the platform. The two objects were placed on either side of a fixation cross (Left and Right).

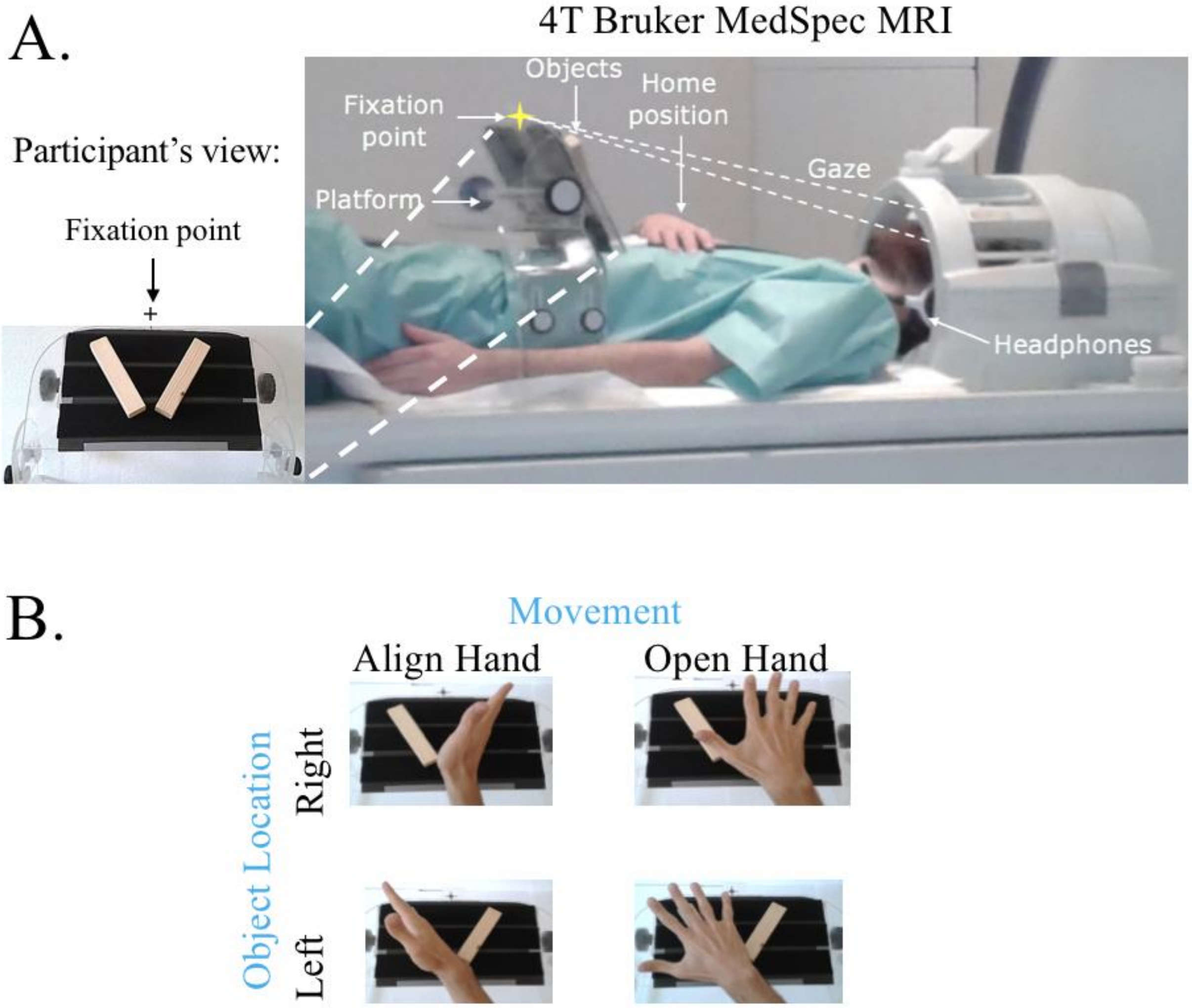


Figure 5.
Experimental setup and stimuli. (A) The setup required participants to gaze at the fixation point, marked with a cross, while preforming the task. Shown on the left side is the participant's view of the platform with the two oriented objects. (B) Four actions were performed by participants based on the condition type. Movements consisted of Align or Open Hand and objects were located on the left or right. As shown here, Align required the precise adjusting of a participant's hand over the object while Open Hand movements were coarse.

The object on the left was oriented at -45° while the one on the right was oriented at 45°. Figure 5B shows the hand actions and object locations. The head of the participant was slightly tilted (~30°) to allow direct viewing of the stimuli presented on the platform. The platform was perpendicular to gaze and approximately 65 cm from the eyes. To limit motion artifacts, the right upper arm was supported with foam and gently restrained. Reaches were thus performed by movements of the right forearm and hand. A button box was placed on the participants' abdomen and served as the starting point for each trial. Hand actions were monitored with a Sony HDR-UX1E digital video camera to confirm that participants were performing the correct tasks during the fMRI experiment. The lights were on throughout the experiment and the hand was visible to participants. Participants wore headphones to hear auditory instructions and cues.

2.2c Experimental Paradigm

We used fMRI to measure the blood-oxygenation-level dependent (BOLD) signal (Ogawa et al., 1992) in a slow event-related delayed-action paradigm. As shown in Figure 6A, each trial began with an auditory cue that indicated the condition type to the participant. There were 4 conditions: Align Hand Left, Align Hand Right, Open Hand Left and Open Hand Right. Then, there was a delay of 10 seconds during which participants did not perform any action until they heard a go cue. When hearing the go cue, participants had 2.5 seconds to perform the movement that they had been instructed to perform at the beginning of the same trial. When they heard a beep, they moved their hand to the button box which was the home position and waited until the next trial began. This inter trial interval (ITI) lasted 12.5 seconds. The next trial began with the condition type. Throughout the whole experiment, participants were instructed to fixate their eyes on the fixation cross between the two oriented objects. The objects were visible to the participants throughout the experiment. Participants only performed actions with their right hand.

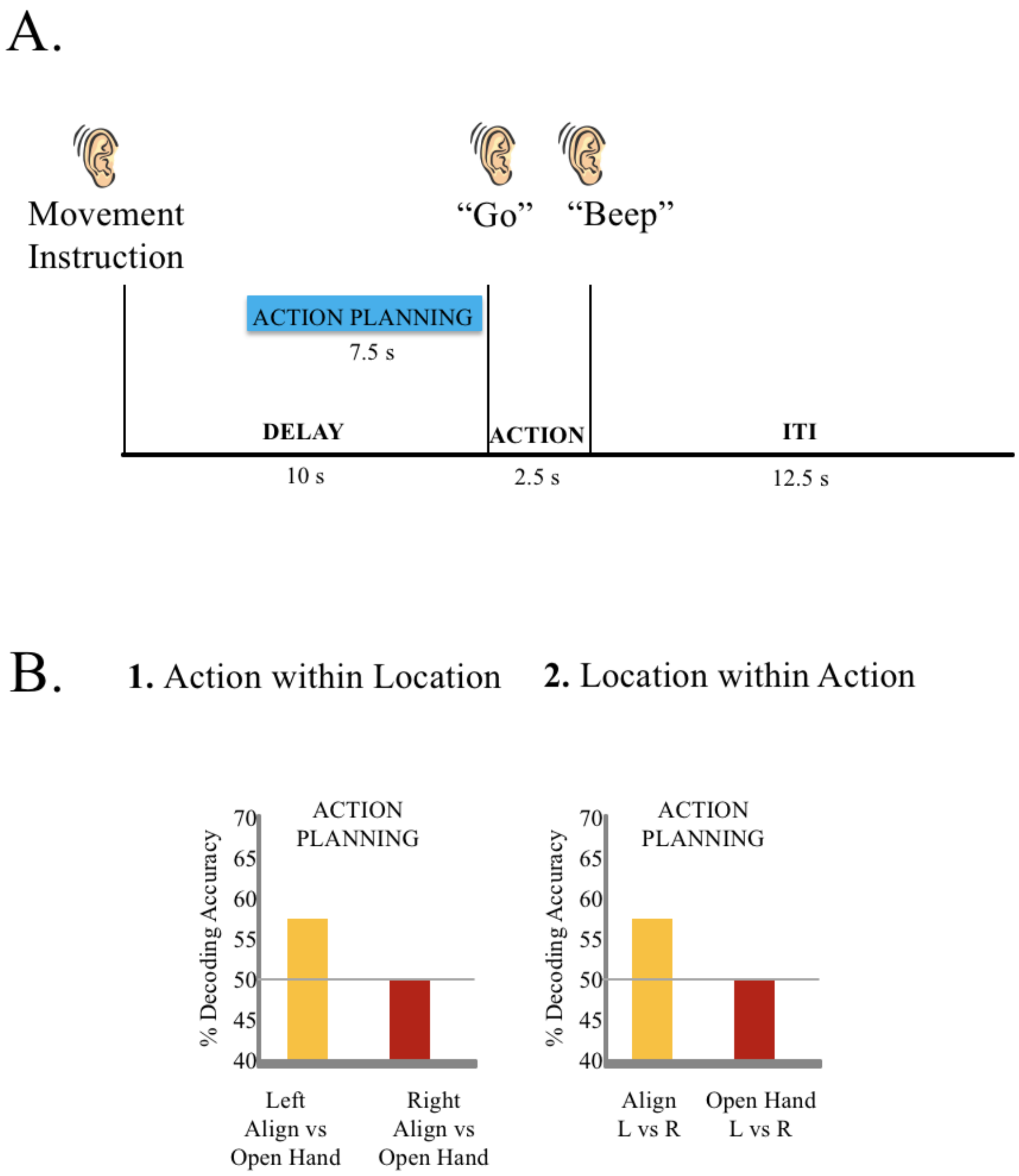


Figure 6.
Experimental paradigm and predictions. (A) At the beginning of each trial, an auditory cue indicated the condition type to the participant (Align Hand Left, Align Hand Right, Open Hand Left and Open Hand Right). There was a delay of 10 seconds during which participants did not perform any action until they heard a go cue upon which they performed the movement that they had been instructed at the beginning of the same trial. The end of the trial was cued by a "beep" sound. We used a 12.5 second intertrial interval. The 7.5 sec of the delay period, before action execution is what we focused analysis on. We did not analyze the whole 10 seconds of the delay as the first part was contaminated by the auditory cue. (B) Predicted percent decoding accuracies based on MVPA for Align and Open Hand movements during action planning. We hypothesized: (1) An action-dependent dissociation in each location, and (2) Modulation of object orientation based on the action.

Align Hand movements consisted of reaching to the oriented object on the left or on the right and adjusting the hand precisely over it. The Open Hand movements consisted of coarse reaching to the oriented object on the right or left with an open palm. Each participant was trained and tested in a short practice session (10-15 minutes) prior to the fMRI experiment.

Therefore, we had a 2 x 2 factorial design, with factors of Movement (Align Hand or Open Hand) and Object Location (Left or Right). This led to 4 condition types in the execution phase: Align Hand Left, Align Hand Right, Open Hand Left and Open Hand Right. There were 7 trials of each type per block for a total of 28 trials per experimental block. On average, participants completed a total of 140 trials (7 trials of each of the 4 conditions). The trials were presented in a randomized order and each trial took 25 seconds to complete. Since there were 28 trials per block, each block lasted ~12 minutes.

2.2d Imaging Parameters

This study was conducted at the University of Trento’s Center for Mind/Brain Sciences (CIMeC) in Mattarello, Italy using a 4T Bruker MedSpec whole body MRI system (Bruker BioSpin, Ettlingen, Germany), equipped with Siemens Magnetom Sonata gradients (200 T/m/s slew rate, 40 mT/m maximum strength; Siemens Medical Solutions, Erlangen, Germany) and an eight-channel head coil. Functional data was acquired using T2*-weighted segmented gradient echo-planar imaging sequence (repetition time [TR] = 2500 ms; echo time [TE] = 33 ms; flip angle [FA] = 78°; field of view [FOV] = 192 × 192 mm, matrix size = 64 × 64 leading to an in-slice resolution of 3 × 3 mm; slice thickness = 3 mm, 0.45mm gap). Each volume was comprised of 35 slices, which were collected in interleaved order. During each experimental session, a T1-weighted anatomical reference volume was acquired using a MPRAGE sequence (TR = 2700 ms; TE = 7°; inversion time TI = 1,020 ms; FA = 7°; FOV = 256 x 224 x 176, 1 mm isotropic resolution).

2.2e Preprocessing

Data was analyzed using Brain Voyager QX software version 2.8.4 (Brain Innovation, Maastricht, Netherlands). The first 3 volumes of each scan were discarded to avoid T1 saturation effects. For each run, slice scan time correction (cubic spline), temporal filtering (removing frequencies <2 cycles/run) and 3D motion correction (trilinear/sinc) were performed. To complete 3D motion correction, each volume of a run was aligned to the volume of the functional scan that was closest in time to the anatomical scan. 7 runs showing head movements greater than 1mm were discarded. Functional data was superimposed on anatomical data, aligned along the anterior commissure-posterior commissure plane, then transformed into Talairach space. Functional data was resampled to 3mm isotropic resolution and anatomical data was resampled to 1mm isotropic resolution in Talairach space.

2.2f General Linear Model (GLM)

Data from the experimental runs were analyzed with a group random-effects (RFX) general linear model (GLM) that included 18 predictors for each participant. There was 1 predictor for each condition and 3 phases: delay, action and audio resulting in a total of 12 predictors of interest. In addition, 6 motion correction parameters as well as predictors for behavioral errors and inter-trial intervals were added as confound errors. Each predictor was derived from a rectangular-wave function convolved with a standard hemodynamic response function (HRF; Brain Voyager QX's default double-gamma HRF). The GLM was performed on %-transformed beta weights (β), so β values were scaled with respect to the mean signal level.

2.2g Voxelwise Analysis

Contrasts were performed on β weights using an RFX (random effects) GLM with a percentage signal change transformation. To determine areas of activation involved in action planning and object orientation, Left over Right contrasts were performed for Align and Open Hand actions. The delayed timing of this experiment allowed us to isolate the pre-movement activity patterns during planning in each ROI.

Activation maps for group voxelwise results were overlaid on the average inflated brains of all participants by cortex based alignment. To correct for multiple comparisons, cluster threshold correction for each activation map was completed using Brain Voyager's cluster-level statistical threshold estimator plug-in. This algorithm applied 1000 iterations of Monte Carlo simulations to estimate the number of neighboring false positive voxels which were active purely due to chance while taking into consideration the average smoothness of the statistical maps. Areas that did not survive were excluded from further analysis.

2.2h Retinotopic Mapping

A separate set of 14 participants underwent retinotopic procedures, of these 4 participated in the experiment. The expanding ring, used for eccentricity mapping, increased logarithmically as a function of time in both size and rate of expansion, so as to match the estimated human cortical magnification function (for details see Swisher, Halko, Merabet, McMains, & Somers, 2007). The smallest and largest ring size corresponded, respectively, to 1° and 10° of diameter. We divided the 10° into 8 equal time bins (of 8 seconds each). Each stimulus type (wedge or ring) was presented in a separate scan of 9 minute duration, and was composed of 8 cycles, each lasting 64 seconds. Retinotopy stimuli were rear-projected with an LCD projector (EPSON EMP

7900 projector; resolution, 1280x1024, 60-Hz refresh rate) onto a screen mounted behind the participant’s head. The participants viewed the images through a mirror mounted to the head coil directly above the eyes. For eccentricity stimuli, we convolved a boxcar-shaped predictor for each bin with a standard HRF and performed contrasts using a Random-Subjects GLM.

We completed eccentricity mapping but not polar angle mapping because our arguments are in terms of the eccentric locations rather than the specific visual areas implicated and the meridia from polar angle maps are less straightforward to combine across participants. Moreover, the discrimination of visual areas within the foveal confluence is rarely done because it is technically challenging (see Schira et al., 2009).

2.2i Imaging Parameters for Retinotopic Mapping

Retinotopic mapping was also conducted at CIMeC using the same 4-T MRI system, Siemens Magnetom Sonata gradients and eight-channel head coil described above. Functional data was acquired using T2*-weighted segmented gradient echo-planar imaging sequence (repetition time [TR] = 2000 ms; echo time [TE] = 33 ms; flip angle [FA] = 73°; field of view [FOV] = 192 × 192 mm, matrix size = 64 × 64 leading to an in-slice resolution of 3 × 3 mm; slice thickness = 3 mm, 0.45mm gap). Each volume comprised 33 slices. During each experimental session, a T1-weighted anatomical reference volume was acquired using a MPRAGE sequence (TR = 2700 ms; TE =7°; inversion time TI = 1,020 ms; FA = 7°; FOV = 256 x 224 x 176; 1 mm isotropic resolution).

2.2j Sessions

The experimental and retinotopic mapping sessions took place on two different days. The experimental session lasted approximately 2 hours, including screening and set-up time, while the retinotopic mapping session took approximately 30 minutes to be completed.

2.2k Regions of Interest (ROIs)

To localize the retinotopic location of our stimuli in the EVC (~8° of visual angle), we ran a contrast of: (bins: 678 > 123). Indeed, bins from 6 to 8 correspond to parafovea and perifovea (from 6.7° to 10.1°), while bins from 1 to 3 correspond to the fovea (up to 4.5°). According to Wandell (1995), the diameter of the fovea is ~5°, while the parafovea and perifovea extending around the fovea have diameters of ~5-9° and ~9-17°, respectively (for a review see also Strasburger et al., 2011). Therefore, in this experiment bins from 1 to 3 correspond to the fovea (up to 4.5°) whereas bins from 6 to 8 correspond to parafovea and perifovea (from 6.7° to 10.1°).

Visual areas such as the calcarine sulcus and occipital pole were localized to determine how the activity pattern elicited by object orientation is enhanced by an action plan. We localized the calcarine sulcus based on the retinotopic location of our stimuli along that sulcus. Since the eccentricity of our visual stimuli was ~8 degrees of visual angle and they were located below the fixation point, we selected our ROI based on the activation map of our retinotopic localizer showing eccentricity between 6.7 and 10 degrees of visual angle (activation shown in green in Figure 7A), and slightly above the calcarine sulcus (consistent with the location of the objects in the lower visual filed). The occipital pole corresponds to the foveal confluence of numerous retinotopic visual areas, specifically V1, V2, V3, hV4, LO-1 and LO-2 (Schira et al., 2009;

Wandell, Dumoulin, & Brewer, 2007). In addition to the ROIs in the EVC, we also identified areas that are typically part of the action network (Figure 7B): superior-parietal occipital cortex (SPOC), anterior intraparietal sulcus (aIPS), posterior intraparietal sulcus (pIPS), lateral occipital cortex (LOC) and dorsal premotor cortex (dPM). SPOC and aIPS play a key role in processing wrist orientation in macaques and humans during action execution (Baumann et al., 2009; Cavina-Pratesi et al., 2010). Moreover, Monaco et al. (2011) found that pIPS and dPM were also recruited for processing wrist orientation in humans. LOC is involved in shape perception and discriminating orientation (Ganel & Goodale, 2017).

ROIs in the dorsal and ventral stream were localized anatomically: the superior end of the parietal occipital sulcus for SPOC; junction of intraparietal and postcentral sulci for aIPS; posterior end of the intraparietal sulcus for pIPS; junction of inferior temporal sulcus and lateral occipital sulcus for LOC; and T-junction of superior frontal and precentral sulci for dPM.

A sphere with a radius of 9 mm was centered at the anatomical location of each area so each ROI consisted of exactly 3071 voxels. Since the number of voxels in each ROI was consistent, a dissociation in MVPA patterns can be attributed to differences in patterns of activation not a difference in the number of voxels. Since these areas are also implicated in action execution (Chen et al., 2014; Culham et al., 2003) for each area, we then ensured that the anatomical localization overlapped with the univariate contrast All Actions > Baseline.

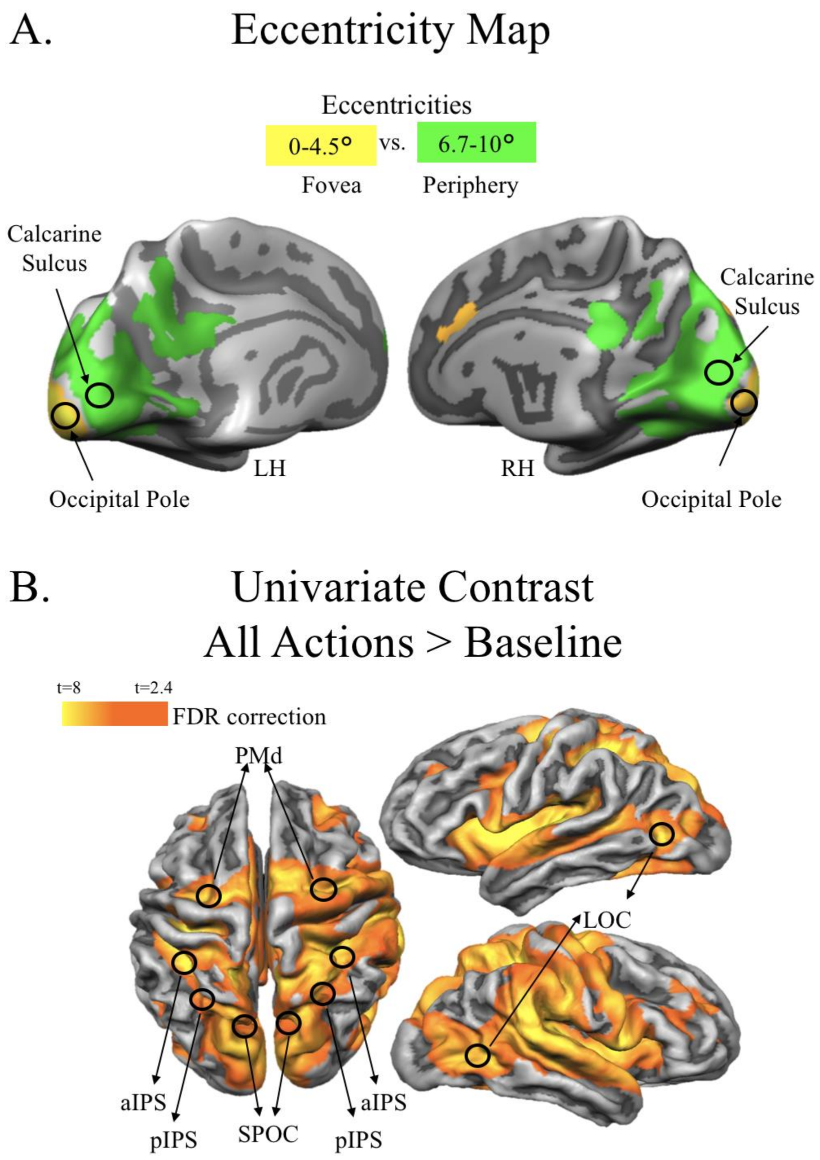


Figure 7.
Activation maps in the EVC and areas of the action network. (A) EVC activation maps for eccentricities from 0 to 10° of visual angles in the occipital pole and calcarine sulcus. Overlap between two activation maps showing: 1) areas with higher activation for 6.7-10° than 0-4.5° (green) and areas with higher activation for eccentricities 0-4.5° than 6.7-10° (yellow). Eccentricity mapping was completed to independently localize the calcarine sulcus (which corresponds to the objects' placement in the visual field) and the occipital pole (which corresponds to the foveal cortex). Eccentricity mapping was completed on a separate set of 14 participants. (B) Dorsal and ventral stream activation maps for the univariate contrast All Actions > Baseline to localize ROIs. Voxelwise statistical maps were obtained with the Random Effects GLM of experimental runs. The activation maps are overlaid on the average cortical surface. Abbreviations: SPOC = superior parietal occipital cortex; pIPS = posterior intraparietal sulcus; aIPS = anterior intraparietal sulcus; PMd = dorsal premotor area; LOC = lateral occipital cortex.

To determine the effect during the Delay phase, for each ROI we extracted the β weights for each participant in each experimental condition. We did not see a difference between Left and Right for Align or Open Hand using the contrasts Delay Align Left > Delay Align Right and Delay Open Hand Left > Delay Open Hand Right. To determine if additional areas of activation existed, a voxelwise contrast was completed using the GLM. This did not reveal any active voxels therefore MVPA was completed on our ROIs.

2.2l Multi-Voxel Pattern Analysis (MVPA)

MVPA was performed to determine if in the EVC: 1) actions modulate activity within object location (Figure 6B, left panel), and 2) object locations modulate the activity within actions (Figure 6B, right panel).We used a combination of in-house software (using MATLAB) and the CoSMo MVPA Toolbox for MATLAB (http://cosmomvpa.org), with an LDA classifier (http://cosmomvpa.org/matlab/cosmo_classify_lda.html#cosmo-classify-lda). We adopted a 'leave-one-run-out' cross-validation approach to test the accuracy of the LDA classifier. We statistically assessed decoding significance across participants with a one-tailed t-test versus 50% chance decoding. We used one-tailed t-tests because we expected the decoding accuracy to be significantly over but not below chance level.

2.2l. i Classifier inputs

To provide inputs for the LDA classifier, the β weights were extracted from the phase of interest (i.e. Delay or Action phase) for each voxel in the ROI. Each phase included the volumes defined in the predictors for the GLM estimated on unsmoothed data. In particular, the Delay phase consisted of 3 volumes following the Instruction phase, while the Action phase consisted of 1 volume following the Delay phase.

2.2m Psychophysiological Interaction (PPI) Analysis

Task-specific changes in functional connectivity were measured using PPI (Friston et al., 1997; McLaren, Ries, Xu, & Johnson, 2012; O'Reilly et al., 2012). PPI identifies brain regions whose functional connectivity is modified by the task beyond correlations based on physiology ("physiological component") and task-modulated activity ("psychological component"). Here, connectivity between seed regions (left and right hemisphere calcarine sulcus) and the rest of the brain during the Delay period were determined. For each participant, a PPI model for each run was created. This included: i) the physiological component of z-normalized time-courses extracted from the seed region, ii) the psychological component, corresponding to the task model where predictors were convolved with a standard HRF, and iii) the "psychophysiological interaction component", resulting from a volume by volume multiplication of the z-normalized time course with the task model. The predictors of the psychological component were set to +1 for the Align Left and Align Right conditions for the Delay Phase, -1 for Open Hand Left and Open Hand Right conditions for the Delay Phase, and zero for baseline and all other conditions. The individual GLM design matrix files were used for a random effects model analysis (Friston et al., 1999).

2.3 Results

The Talairach coordinates and numbers of voxels of each ROI are specified in Table 1. Activation maps and activation levels for each ROI are shown in Figure 7. We used retinotopic mapping to localize the peripheral representations of the objects in the visual retinotopic cortex as well as the foveal cortex using an independent sample of 14 participants. As shown in Figure 7A, the calcarine sulcus showed higher activation for eccentricities corresponding to the periphery (6.7-10°) than the fovea (0-4.5°). In contrast, the occipital pole showed higher activation for eccentricities corresponding to foveal vision than the periphery. We used the univariate contrast All Actions > Baseline to localize areas that are part of the action network (Figure 7B).

Table 1. Talairach coordinates for each ROI.

	Talairach coordinates		
ROI Name	**x**	**y**	**z**
LH Calcarine sulcus	-6	-82	-1
RH Calcarine sulcus	6	-82	0
LH Occipital pole	-9	-91	-12
RH Occipital pole	12	-90	-6
LH Superior parieto-occipital cortex	-16	-81	32
RH Superior parieto-occipital cortex	15	-79	37
LH Posterior intraparietal sulcus	-30	-47	44
RH Posterior intraparietal sulcus	30	-47	44
LH Anterior intraparietal sulcus	-43	-37	39
RH Anterior intraparietal sulcus	42	-41	41
LH Dorsal premotor cortex	-27	-16	54
RH Dorsal premotor cortex	27	-16	57
LH Lateral occipital cortex	-43	-66	-6
RH Lateral occipital cortex	39	-66	-4

Note: LH: left hemisphere; RH: right hemisphere.
Talairach coordinates refer to the peak activation of the functional cluster.

In contrast to the execution phase results shown in Figure 7B, univariate analyses for the planning phase did not reveal any active voxels for the contrasts: Align Left > Align Right nor Open Hand Left > Open Hand Right. Figure 8 shows the time courses from ROIs in the EVC and two representative time courses of the action network from left SPOC and left pIPS. There was no significant difference between conditions during the delay period (Figure 8) and this was the case for other ROIs as well. Therefore, this motivated the use of MVPA to decode action intention in the EVC.

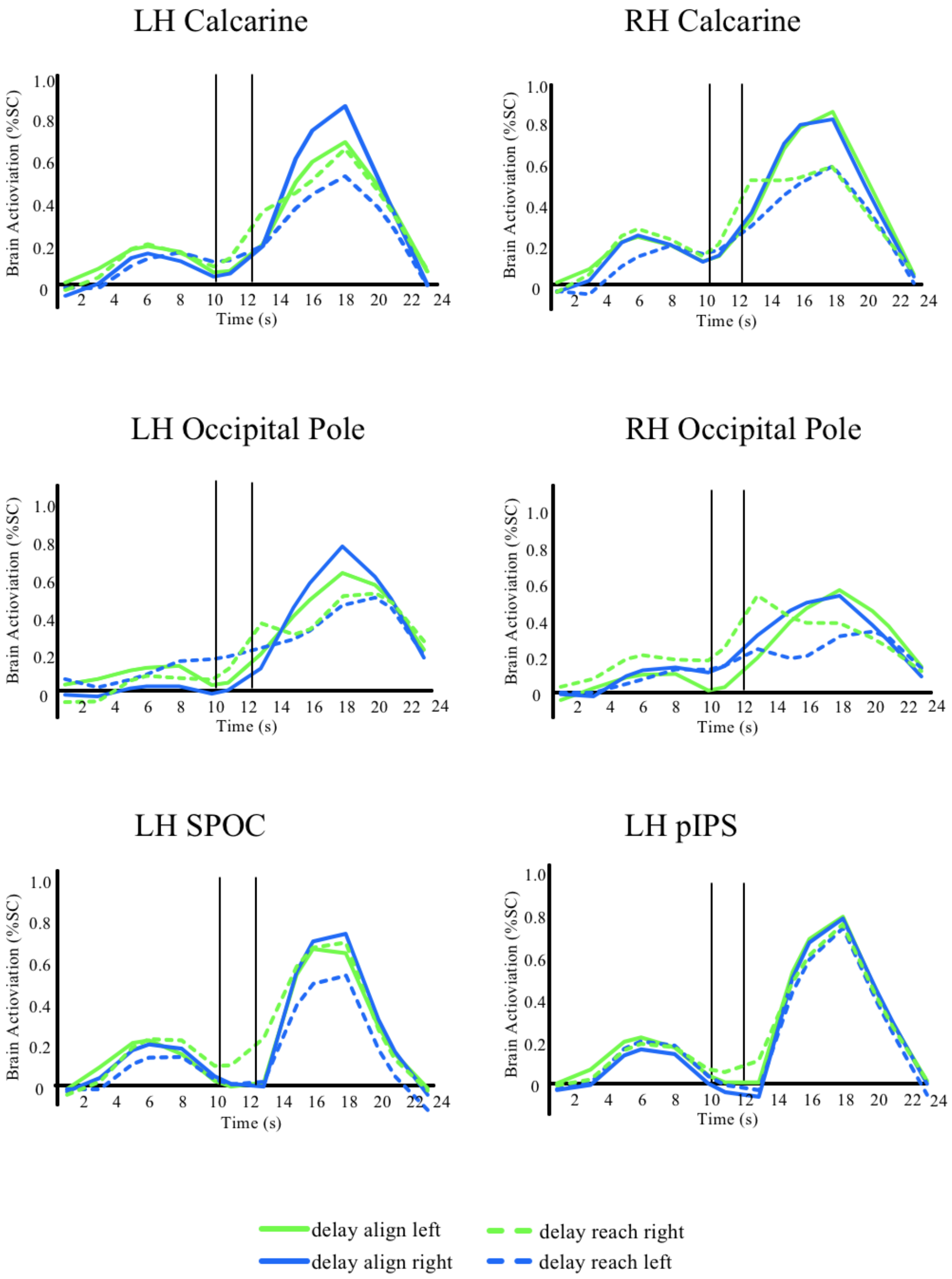
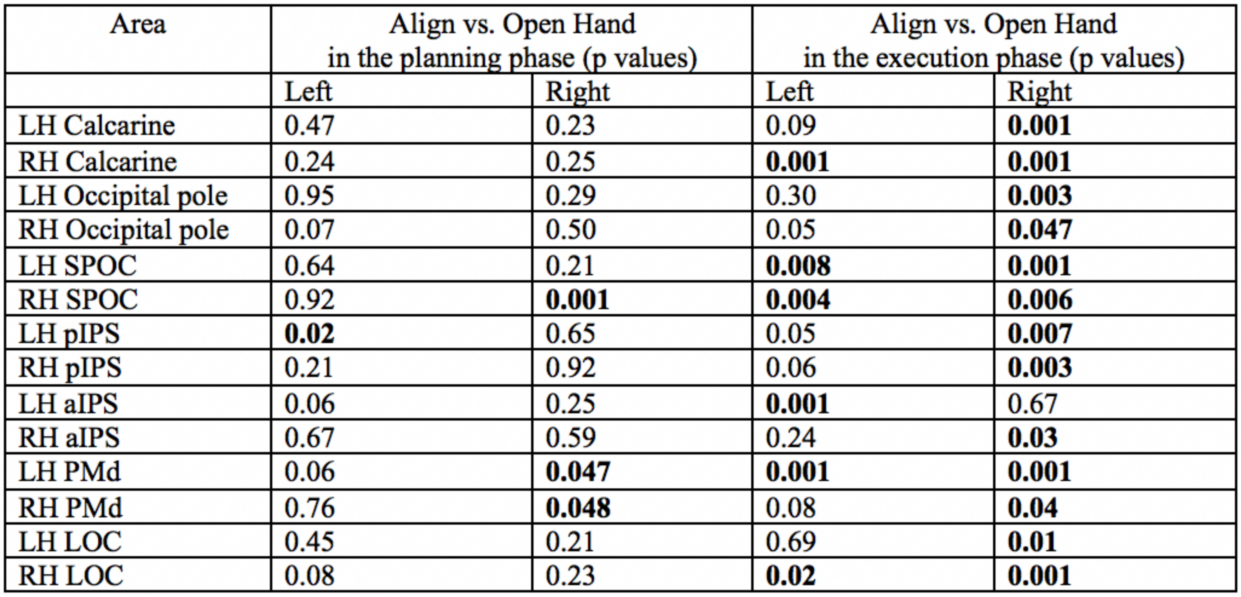


Figure 8.
Time courses for EVC and action network ROIs showing averaged neural activity, time locked to the start of an experimental run. Brain activation in percent signal change is indicated for each condition. The vertical lines indicate the onset of the action and intertrial interval (from left to right). The EVC ROIs of the calcarine sulcus and occipital pole were localized by eccentricity mapping. We localized left SPOC and left pIPS using the univariate contrast All Actions > Baseline.

2.3a MVPA

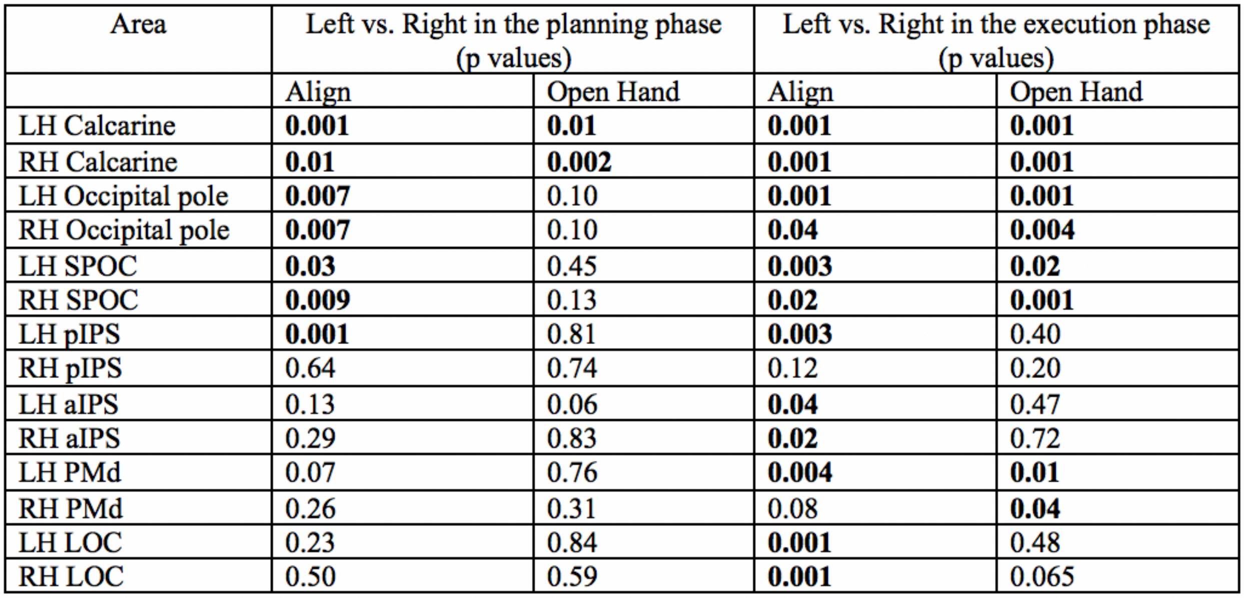
Statistical values for each comparison are specified in Tables 2 and 3.

Table 2. Statistical values for the Action within Location analyses.



Area	Align vs. Open Hand in the planning phase (p values)		Align vs. Open Hand in the execution phase (p values)	
	Left	Right	Left	Right
LH Calcarine	0.47	0.23	0.09	**0.001**
RH Calcarine	0.24	0.25	**0.001**	**0.001**
LH Occipital pole	0.95	0.29	0.30	**0.003**
RH Occipital pole	0.07	0.50	0.05	**0.047**
LH SPOC	0.64	0.21	**0.008**	**0.001**
RH SPOC	0.92	**0.001**	**0.004**	**0.006**
LH pIPS	**0.02**	0.65	0.05	**0.007**
RH pIPS	0.21	0.92	0.06	**0.003**
LH aIPS	0.06	0.25	**0.001**	0.67
RH aIPS	0.67	0.59	0.24	**0.03**
LH PMd	0.06	**0.047**	**0.001**	**0.001**
RH PMd	0.76	**0.048**	0.08	**0.04**
LH LOC	0.45	0.21	0.69	**0.01**
RH LOC	0.08	0.23	**0.02**	**0.001**

Table 3. Statistical values for the Location within Action analyses.



Area	Left vs. Right in the planning phase (p values)		Left vs. Right in the execution phase (p values)	
	Align	Open Hand	Align	Open Hand
LH Calcarine	**0.001**	**0.01**	**0.001**	**0.001**
RH Calcarine	**0.01**	**0.002**	**0.001**	**0.001**
LH Occipital pole	**0.007**	0.10	**0.001**	**0.001**
RH Occipital pole	**0.007**	0.10	**0.04**	**0.004**
LH SPOC	**0.03**	0.45	**0.003**	**0.02**
RH SPOC	**0.009**	0.13	**0.02**	**0.001**
LH pIPS	**0.001**	0.81	**0.003**	0.40
RH pIPS	0.64	0.74	0.12	0.20
LH aIPS	0.13	0.06	**0.04**	0.47
RH aIPS	0.29	0.83	**0.02**	0.72
LH PMd	0.07	0.76	**0.004**	**0.01**
RH PMd	0.26	0.31	0.08	**0.04**
LH LOC	0.23	0.84	**0.001**	0.48
RH LOC	0.50	0.59	**0.001**	0.065

2.3a. i Action within Location

Figures 9 and 10 show the mean classification accuracy in each ROI for pairwise comparisons for Align versus Open Hand movements to the left and right target locations (Action within Location). For instance, for the object on the left side we trained and tested the classifier on the dissociation between Align and Open hand movements, and did the same for the object on the right side.

For the ROIs in the EVC (Figure 9), in the planning phase there was no significant decoding accuracy for Align versus Open Hand movements for left as well as right object locations. In the execution phase, there was a significant decoding accuracy for the dissociation between the two movements for the right object location in bilateral calcarine sulcus and occipital pole. The right calcarine sulcus also showed a significant decoding accuracy for the two movements for the left object location.

As shown in Figure 10, in the planning phase we found an above chance decoding accuracy for Align versus Open Hand movements in left pIPS for the left object location, and right SPOC as well as bilateral PMd for the right object location. In the execution phase, we found an above chance decoding accuracy for the left object location in bilateral SPOC, left aIPS, left PMd and right LOC. In addition, for the object on the right there was a significant decoding accuracy for Align versus Open Hand for bilateral SPOC, pIPS, PMd, LOC and right aIPS.

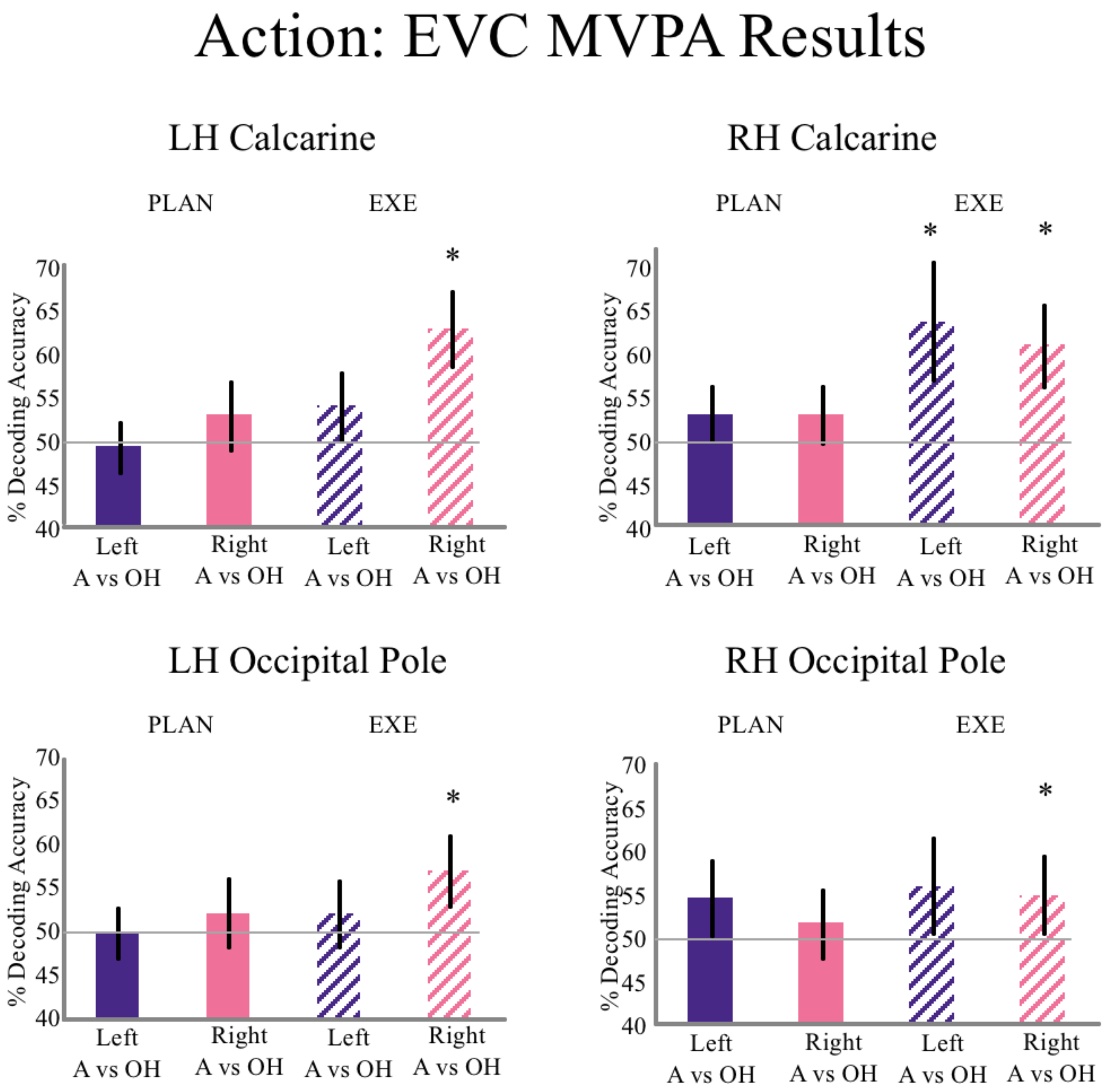


Figure 9.
Action-dependent dissociation in left and right object locations in EVC areas. Bar graphs indicate the MVPA results for the calcarine sulcus and occipital pole. Percent decoding accuracy is shown for the Phase (Plan, Execution) and the Location for each movement (A = Align, OH = Open Hand). Error bars indicate 95% confidence intervals. Solid grey lines are chance level accuracy (50%). Black asterisks show statistical differences among conditions for corrected p value.

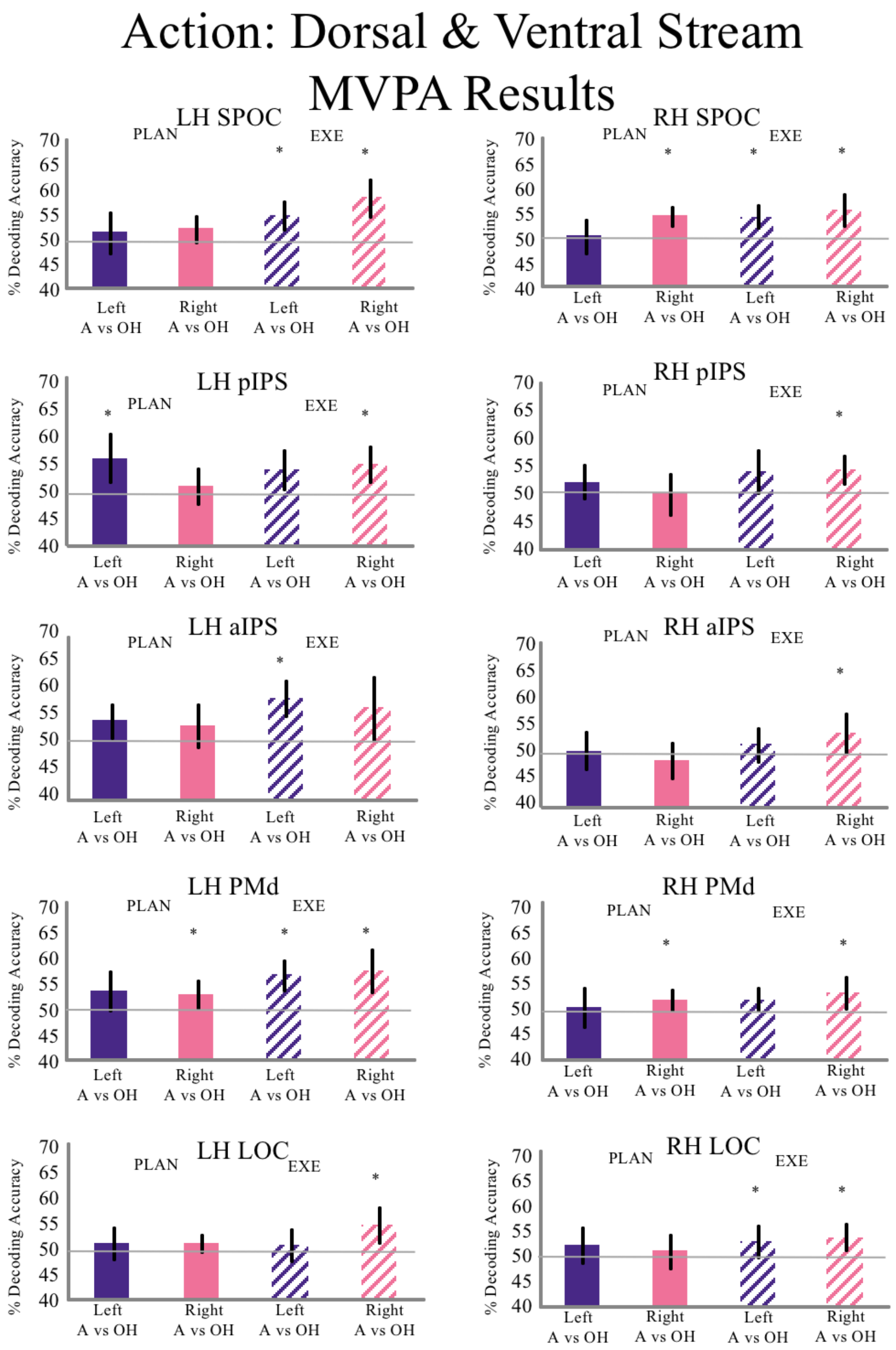


Figure 10.
For each area of the dorsal and ventral stream, MVPA results for an action-dependent dissociation in object location is shown. Percent decoding accuracy is shown for the Phase (Plan, Execution) and the Location for each movement (A = Align, OH = Open Hand). Error bars indicate 95% confidence intervals. Solid grey lines are chance level accuracy (50%). Black asterisks show statistical differences among conditions for corrected p value. Abbreviations: SPOC = superior parietal occipital cortex; pIPS = posterior intraparietal sulcus; aIPS = anterior intraparietal sulcus; PMd = dorsal premotor area; LOC = lateral occipital cortex.

2.3a. ii Location within Action

Figures 11 and 12 show the percent decoding accuracy in each ROI for pairwise comparisons of object orientation (+45 vs. -45) within Align and Open Hand movements (Location within Action). Specifically, for the Align trials we trained and tested the classifier on the dissociation between Left (-45) and Right (+45) object locations, and did the same for Open Hand.

For the ROIs in the EVC (Figure 11), in the planning phase, we found a significant decoding of object orientation for Align and Open Hand movements in the left and right calcarine sulcus. Interestingly, the occipital pole showed an above chance decoding accuracy for Align but not Open Hand movements in the left and right hemisphere. In the execution phase, we found a significant decoding of object orientation for both Align and Open Hand Movements in the calcarine sulcus as well as the occipital pole in the left and right hemisphere.

In sum, we found a representation of object orientation in the occipital pole even though participants were looking at a fixation point instead of the objects themselves, suggesting that the retinotopic cortex feeds back to the EVC.

As shown in Figure 12, in the planning phase, bilateral SPOC and left pIPS showed a significant dissociation of object orientation during the Align but not Open Hand condition. There was no dissociation for object orientation during the planning phase for Align nor Open Hand movements in the right pIPS, bilateral aIPS, bilateral PMd and bilateral LOC. In the execution phase, we found a significant decoding of object orientation for both Align and Open

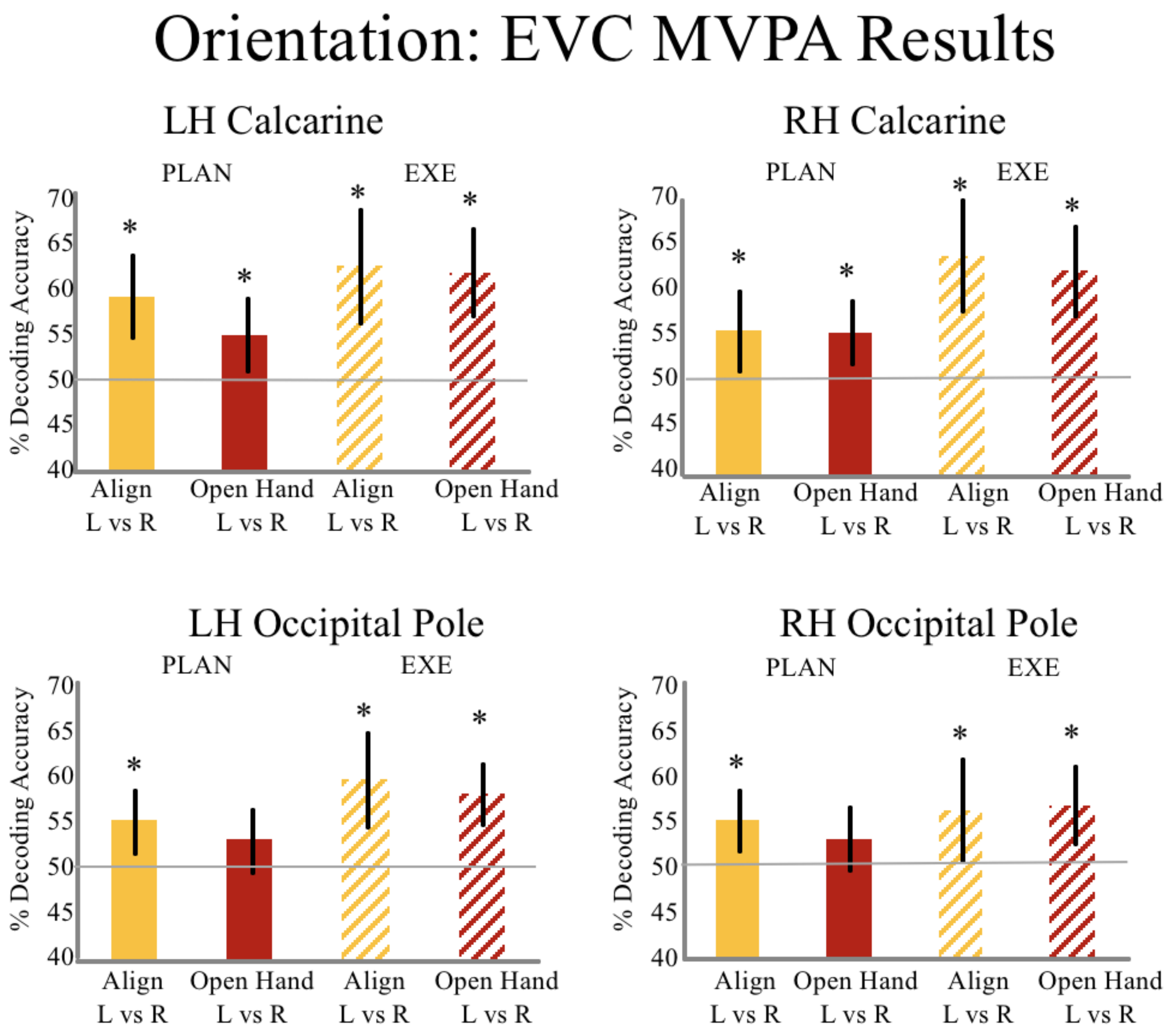


Figure 11.
MVPA results for the dissociation of orientation within the calcarine sulcus and occipital pole. Percent decoding accuracy is shown for the Phase (Plan, Execution) and the Action (Align Left versus Right, Open Hand Left versus Right). Error bars indicate 95% confidence intervals. Solid grey lines are chance level accuracy (50%). Black asterisks show statistical differences among conditions for corrected p value.

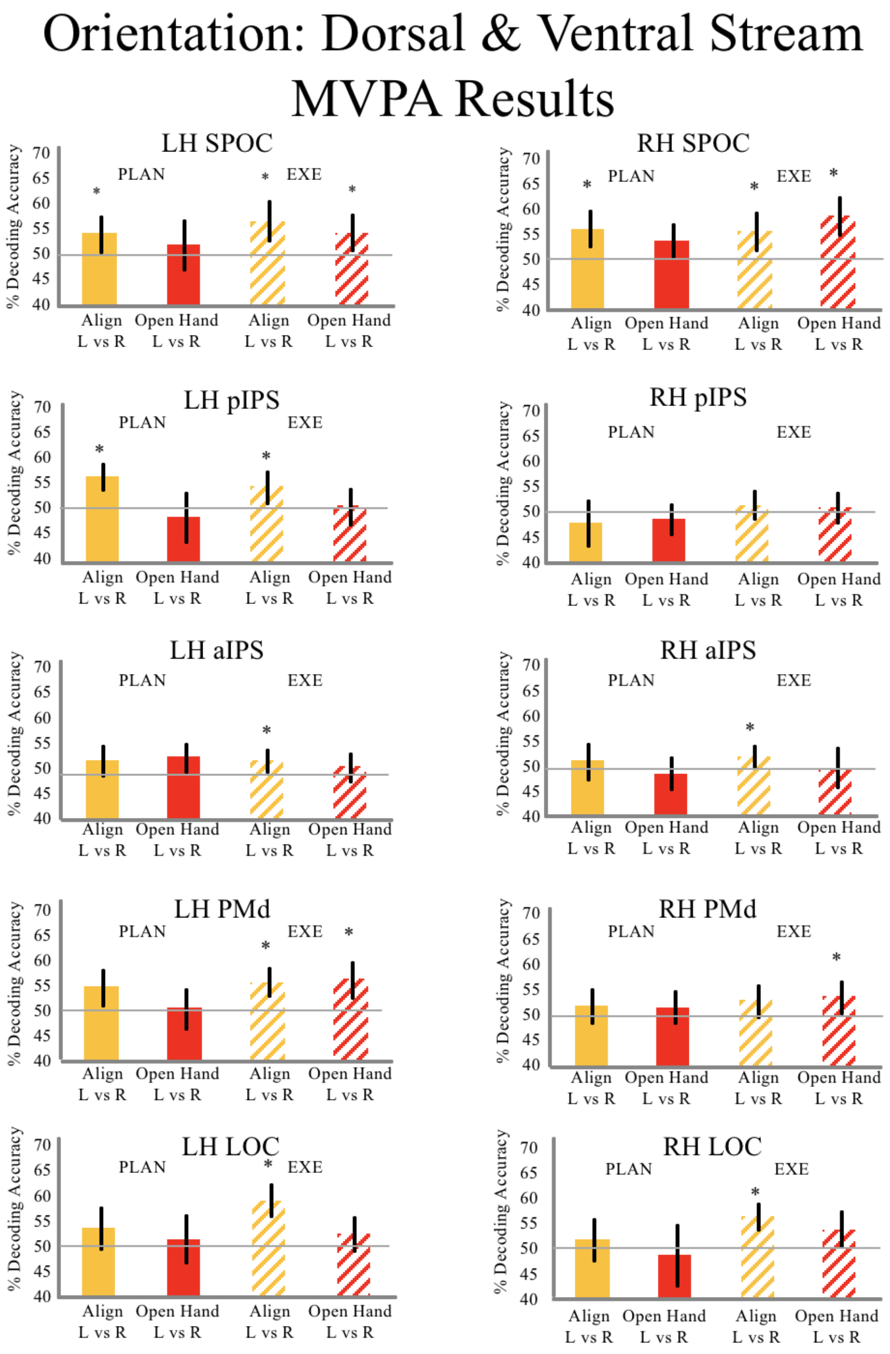


Figure 12.
Decoding orientation for action in dorsal and ventral stream areas. Percent decoding accuracy is shown for the Phase (Plan, Execution) and the Task (Align, Open Hand). Error bars indicate 95% confidence intervals. Solid grey lines are chance level accuracy (50%). Black asterisks show statistical differences among conditions for corrected p value. Abbreviations: SPOC = superior parietal occipital cortex; pIPS = posterior intraparietal sulcus; aIPS = anterior intraparietal sulcus; PMd = dorsal premotor area; LOC = lateral occipital cortex.

Hand movements in SPOC bilaterally and left PMd. Additionally, we could dissociate object orientation for Align but not Open Hand movements in the left pIPS, bilateral aIPS and bilateral LOC.

2.3b PPI Analysis

To test whether connectivity between early visual areas and other regions is modulated in a task-dependent manner by the planned movement, we used PPI. We used the calcarine sulcus as the seed region since it corresponds to the peripheral cortex where objects were placed.

As shown in Figure 13, we found that the left calcarine sulcus showed stronger connections for planning the Align than Open Hand movement with numerous areas including those implicated in the sensory-motor control of grasping actions (right aIPS, right pIPS), multimodal recognition of objects (bilateral LOC), motor control (left SMA) and motor/somatosensory function (left M1/S1). The right calcarine sulcus showed stronger connections for planning the Align than Open Hand movement with the right pIPS, left LOC, left SMA and left M1/S1. However, after completing cluster threshold correction, only the connections between the calcarine sulcus with left M1/S1 and left SMA survived. Taken together, the PPI results reinforce that early visual areas are more strongly connected to somatomotor areas for planning an Align versus Open Hand movement.

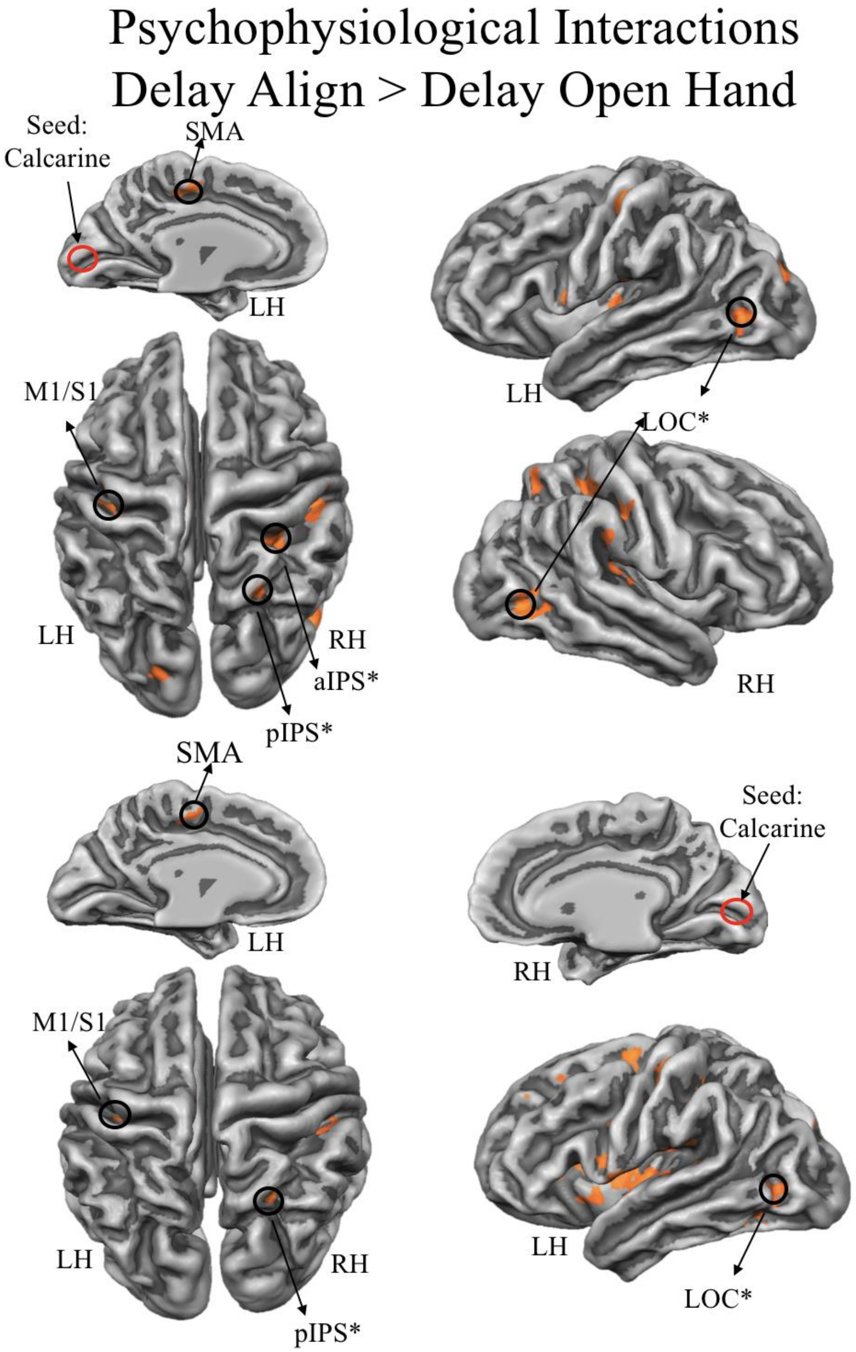


Figure 13.
Functional network of areas connected to the calcarine sulcus during Delay Align versus Delay Open Hand. Statistical parametric maps showing the psychophysiological interaction results using the calcarine sulcus in the left and right hemisphere as seed regions. Black asterisks correspond to areas that did not survive cluster threshold correction. Abbreviations: SMA = supplementary motor area; M1/S1 = primary motor cortex/ primary somatosensory cortex; pIPS = posterior intraparietal sulcus; aIPS = anterior intraparietal sulcus; LOC = lateral occipital cortex.

2.4 Discussion

Though univariate analysis (Figure 8) and MVPA (Figure 9 and 10) did not reveal a significant difference between action type during planning, our main question was aimed to examine whether there was a differential decoding of object orientation when planning an action (Figure 6B, right panel). In the calcarine sulcus, corresponding to the location of the objects, there was a dissociation for the two object orientations, regardless of the upcoming action. Strikingly, in the occipital pole, bilateral SPOC and left pIPS, there was a dissociation for object orientation for Align but not Open Hand movements (Figures 11 and 12). This suggests that upcoming actions enhance the perception of object properties that are relevant for the particular action. Moreover, PPI illustrates that the calcarine sulcus is more strongly connected with somatosensory and motor areas during the planning phase for Align than Open Hand movements suggesting cross talk between EVC and somatomotor areas even during action preparation, the time before a movement is executed. Taken together, these results provide a whole-brain, network-level framework for understanding how sensory information is cortically distributed and processed during action planning.

2.4a The Representation of Orientation is Shaped by Action Intention

To our knowledge, this is the first study to illustrate connections between higher-level motor control areas and the EVC during the planning phase preceding an action. Behavioral and neuroimaging research have revealed that the processing of action-relevant features can be enhanced during movement preparation and relies on areas such as the visual cortex (Bekkering & Neggers, 2002; Cappadocia et al., 2017; Chen et al., 2014; Gutteling et al., 2015; van Elk et al., 2010). Interestingly, we could dissociate object orientation as a function of the upcoming action in the occipital pole, which corresponds to central vision. This is surprising given that the objects were placed below the fixation point (peripheral vision). In particular, MVPA revealed that during planning in the calcarine sulcus (which corresponds to the objects' placement in the visual field), there was a significant decoding of object orientation regardless of action type, while in the occipital pole (which corresponds to the foveal cortex) we could decode object orientation in a task-dependent manner, with an above chance decoding accuracy for object orientation only in the Align task. Retinotopic foveal cortex has been shown to contain visual information even about objects presented in the visual periphery and this phenomenon has been found to correlate with task performance and to be critical for extra-foveal perception (Chambers, Allen, Maizey, & Williams, 2013; Williams et al., 2008). We show that during planning, the enhancement of relevant visual information such as orientation differs in an action-dependent way. The Align action required an adjustment of the hand to the orientation of the object, modulating the representation of object orientation in the occipital pole. Conversely, a coarse movement, such as opening the hand above the object, did not influence the representation of object orientation. This is likely because that information is not needed to successfully plan and execute the action.

Dorsal and ventral stream areas were also dissociated during action preparation. We found a significant decoding accuracy for orientation during planning in SPOC bilaterally and left pIPS for Align but not Open Hand movements. Studies in both humans and monkeys have reported that SPOC plays a key role in processing wrist movements during action planning (Chen et al., 2014; Fattori et al., 2010; Gallivan, McLean, Smith, & Culham, 2011; Monaco et al., 2011; Vesia & Crawford, 2012). Moreover, pIPS encodes 3D visual features of objects for hand actions (Sakata et al., 1998) and plays a role in adjusting wrist and hand orientation

(Monaco et al., 2011). For aPIS, there was no dissociation for orientation during the planning phase of Align or Open Hand movements. Previous studies have shown that during movement execution, aIPS shows more activation for grasp than any other movement and it is highly involved in the preshaping of the fingers (Cavina-Pratesi et al., 2010; Culham et al., 2003; Monaco et al., 2017). The fact that we did not use grasping actions might have led to less recruitment of aIPS during the planning phase. However, during execution, in aIPS there was a significant decoding accuracy for orientation in Align but not Open Hand movements as this area orients the wrist during a movement (Baumann et al., 2009; Murata et al., 2000). Though we did not decode activity during the planning phase in PMd, this is in line with other studies which found differences in PMd between grasping and reaching during the execution phase of a movement (Cavina-Pratesi et al., 2010; Culham et al., 2003; Gallivan et al., 2011) as its activity is modulated during object grasping (Raos, 2005), by grasp- relevant object properties (Grol et al., 2007; Verhagen, Dijkerman, Grol, & Toni, 2008) and the grip force scaling required (Hendrix, Mason, & Ebner, 2009). Since we could only decode Align but not Open Hand in LOC during execution, this indicates that at the time of action execution, perceptual structures involved in object recognition are recruited to provide relevant information about object properties to guide the dorsal stream in performing the action (Monaco et al., 2017; Singhal et al., 2013).

2.4b Psychophysiological Interactions: Functional Connectivity During Action Planning

It is possible that actions differentially modulate EVC areas because of differential connectivity. Previous findings have shown connections between frontoparietal areas and early visual areas (Moore & Fallah, 2004; Ruff et al., 2006, 2008). One should expect a stronger connectivity between higher-level cortical areas and EVC areas for Align but not Open Hand tasks. Indeed, our PPI analysis revealed that for Align versus Open Hand, the calcarine sulcus is more strongly connected to somatomotor areas such as the left M1/S1 and left SMA. This, again, might be explained by the fact that Align movements require more adjustments than coarse Open Hand movements. A previous study has shown functional connections between LOC and S1 however, this was while a participant's hand was tactilely stimulated (Tal et al., 2016). In addition, Monaco and colleagues (2017) found stronger functional connectivity between the occipital pole with S1 and dorsal stream areas while participants' haptically explored objects. We demonstrate a task-dependent functional connectivity exists even before action execution, before any tactile stimulation. Our study sheds light into a mechanism illustrating cross-talk between EVC and somatomotor areas exist not only during sensory feedback but also underlying action preparation.

2.4c Functional Significance for Behavior

We filter feature information from redundant stimuli in the world around us to successfully plan actions. The feedback connections illustrated in this study may help with sensory gating. Moreover, the planning of actions elicits motor, somatosensory and proprioceptive responses, allowing for error detection and motor learning. For example, Perry, Sergio, Crawford, and Fallah (2015) showed that the receptive fields of V2 neurons displayed enhanced orientation selectivity due to the presence of a nearby hand. Behavioral and neural evidence has shown that attention is directed to the location of a planned movement (Bekkering and Neggers, 2002; Moore and Fallah, 2004). Since there is a tight linkage between attention and action planning, researchers have suggested that these processes are subserved by the same neural mechanisms (Rizzolatti, Riggio, Dascola, & Umilta, 1987). The dissociation of attention from action planning (intention) have been attempted. It has been suggested that if the neuronal responses that form prior to movement were due to spatial attention alone, they should fail to discriminate effector type such as eye versus limb or right versus left limb (Gallivan et al., 2013). In our study, the dissociation of Align versus Open Hand should have been possible using Action within Location MVPA as Align movements were more difficult to prepare and required more attention. Since this was not the case, we suggest that attention alone does not drive modulation. Motor imagery may play a role in the case of remembered targets as it recruits similar circuits to those of real action execution. Motor imagery may help to remember a target location (Chen et al., 2014). However, imagery alone is not responsible for the reactivation of areas during delayed actions as Monaco and colleagues (2017) showed higher activation during action execution than imagery for visual areas and areas of the action network. We believe that these explanations do not undermine our interpretation of the modulation of object orientation in an action dependent manner during planning.

2.4d Eye Movements Unlikely to Explain Retinotopic Effects

It is unlikely that our results showing higher foveal activation during planning for Align but not Open Hand movements are due to task-related eye movements. Although we did not record eye movements during this experiment, Gallivan and colleagues (2013) conducted a behavioral study using univariate and multivariate analyses to examine fixation when: 1) objects were presented in the lower visual field, 2) participants planned actions towards an object and 3) executed actions in the dark. Participants, including naive ones could reliably fixate on a point for long intervals during each phase of a trial (Gallivan et al., 2013).

2.4e Disentangling Object Features Driving Modulation

For areas that show a dissociation for Align versus Open Hand in both left and right object locations (i.e., the calcarine sulcus) we cannot disambiguate whether object location or orientation drives the modulation. Indeed, both these properties might contribute to successful decoding. However, in areas that show a dissociation of object location for Align but not Open Hand such as the occipital pole, bilateral SPOC and left pIPS, it is likely that object orientation allows for decoding as it is relevant for Align movements but not coarse Open Hand movements. Moreover, when directly comparing Align to Open Hand using Location within Action MVPA, we did not get a significant difference.

2.4f Motivation for MVPA

We conducted MVPA as univariate analysis of the planning phase using the contrasts Left over Right for Align and Open Hand did not produce significant results. It is possible that this is due to the lack of sensitivity of univariate techniques, especially for analyzing the planning phase. Previous fMRI studies that aimed to determine the cortical areas involved in action planning using conventional analysis have been met with mixed degrees of success. This could be because univariate analysis compares response amplitudes and examines voxels independently (Haxby et al., 2001; Kamitani & Tong, 2005; Kriegeskorte & Bandettini, 2007). Instead, by decoding signals, we can determine the areas underlying planning and the different roles played by these areas, advancing previous notions of contributions to movement (Filimon, 2010).

2.4g The Representation of Action Type During Planning

When using MVPA to dissociate action type based on location during the planning phase, we did not get significant decoding accuracies in most areas. However, Gallivan and colleagues (2011, 2013) showed significant decoding accuracies for grasp but not reach in dorsal and ventral stream areas during planning. These two movements are more different from each other than the movements in our study of Align and Open Hand. Grasping requires the movement of the fingers and manipulation of the objects while Align movements do not involve direct object interaction. Though we did not get significant decoding accuracies for Action within Location during the planning phase, during execution, several areas did show a dissociation between action types within object location. This would be expected since participants saw their hand moving in the periphery of the lower visual field while making the movement.

2.4h Conclusion

To conclude, we decoded object orientation regardless of action in the retinotopic cortex corresponding to the location of the objects. For the foveal cortex, during the planning phase preceding the action, we dissociated object orientation in an action-dependent manner. We believe this is due to the precise adjustment of the hand for Align actions, which modulates key object features such as orientation. These results suggest a role of the EVC in predictive coding of actions based on internal models that take into account visual and somatosensory anticipations for upcoming movements. In our everyday lives, we not only see ourselves moving our hand, but somatosensory and proprioceptive responses are elicited by the movement as well. Therefore, we have a lifetime of experience where we have learned how a movement looks and feels. Naturally, visual and somatosensory processing for action do not happen in isolation, in fact these pieces of information are well synchronized when we move. Because of this, it is possible that we built associations between visual and somatosensory information with the corresponding cortical areas that need to exchange information to generate an effective action. This suggests that actions modulate perception and the role of EVC goes beyond visual processing, playing a role in the visual anticipation of a movement.

CHAPTER 3

GENERAL DISCUSSION

3.0 Discussion

In this chapter, I will discuss how our results have contributed to the field of motor control and action planning. I will also discuss future directions, questions that remain from our study and applications of our work.

3.1 Contributions to Literature on Action Planning

Previous research has focused on feedforward connections that arise in the occipital lobe and go through the frontoparietal reaching and grasping networks. In particular, SPOC, mIPS and PMd have been implicated in pointing and reaching, whereas aIPS and PMv have shown grasping-related responses (Binkofski et al., 1998; Culham et al., 2003; Grafton, Fagg, Woods, & Arbib, 1996). To perform a goal-directed action, feedforward processes convert the representation of the object into muscular contractions required for movement (Blohm & Crawford, 2007; Blohm, Keith, & Crawford, 2009). Although studies indicate that the PPC plays an important role in the visuomotor transformations required for reaching and grasping, little is known about the influence of action intentions on the selection of information in the visual system. Only recently have researchers began to ask how perception is modulated by actions. To perform an action successfully, action-relevant features of an object must be enhanced. A behavioral study found increased occipital activation before grasping compared to pointing, suggesting that the intention to grasp influences the processing of features relevant to perform the action (van Elk et al., 2010). Even when actions were only prepared and not executed, action-dependent decoding was possible in the EVC (Gutteling et al., 2015). The enhancement of action-relevant features relies on feedback connections between motor and visual brain areas. For example, when applying TMS to a dorsal stream area, aIPS, orientation sensitivity was modulated during grasping (Gutteling et al., 2013). Functional connections between the occipital pole and the action network have been illustrated however, this was during interaction with an object (Monaco et al., 2017). Interestingly, studies that used multivariate techniques to investigate action planning have uncovered extensive activation in both dorsal and ventral stream (Gallivan et al., 2013). Therefore, top-down signals functionally aimed at perceiving object features optimally facilitate action planning.

Previous studies compared grasping to pointing, allowing for the brain areas recruited for action planning to be determined. Our study investigated the neural mechanism that enhances object orientation by action planning. We used neuroimaging to determine how higher-level cortical areas are connected to EVC. In particular, we examined the delay period between auditory instruction and action execution to determine if connectivity is enhanced when planning Align as compared to Open Hand movements. Though univariate analysis did not produce significant results, using MVPA, we found an above chance decoding accuracy of object orientation regardless of action type during planning in the calcarine sulcus, corresponding to the location of the objects in peripheral vision. Interestingly, we found a significant decoding accuracy for Align but not Open Hand movements during planning in the occipital pole, corresponding to the foveal cortex. We also decoded object orientation in Align but not Open Hand tasks in SPOC and left pIPS. Since we found that orientation was better decoded in one action over another, we then determined how this was possible by using PPI. We found stronger connections between visual and somatomotor brain areas for Align versus Open Hand tasks. During action preparation, the EVC enhances action-relevant features possibly through feedback connections with motor areas. Overall, these results illustrate the cortical distribution and processing of sensory information during planning at the whole-brain network level (Figure 14).

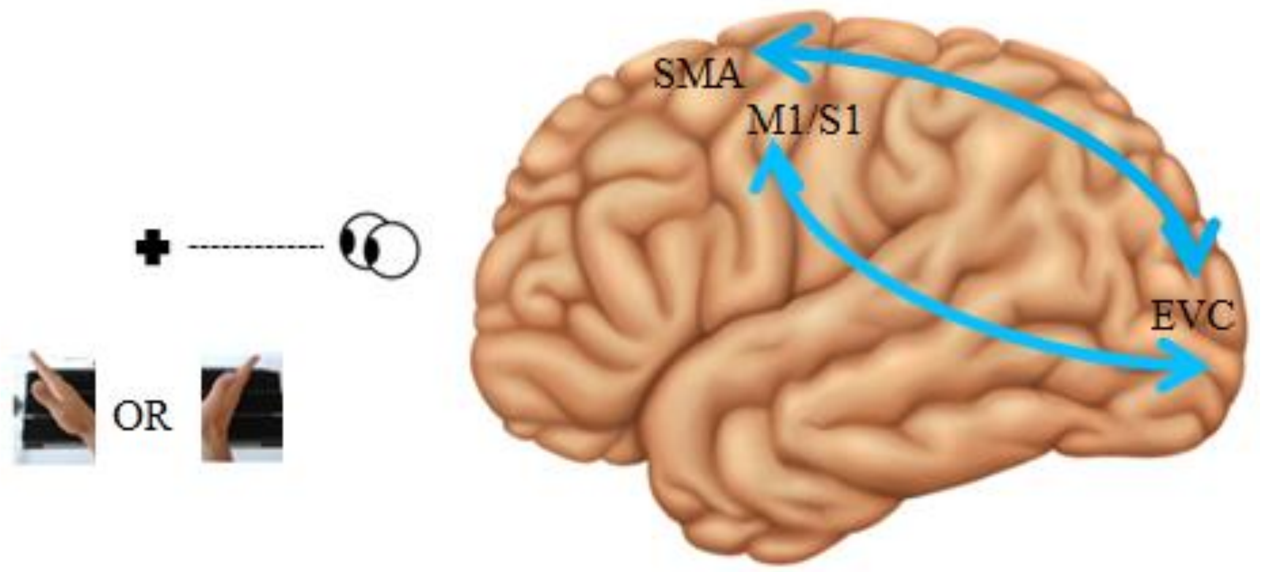


Figure 14.
Summary of our results illustrating that feedforward and feedback connections exist between the visual cortex and somatomotor areas. Feedback connections allow for object features such as orientation to be enhanced in an action-dependent manner. This connectivity exists while participants gazed at the fixation point and prepared, prior to execution, an Align movement to the object oriented at -45° or +45°.

3.2 Future Directions

Our results show that the activity pattern for object orientation is modulated by action through connections between higher-level cortical areas and the EVC. However, there are questions that still remain from this study.

Though strong connections exist between EVC and somatomotor areas during the planning of Align versus Open Hand tasks, what is the directionality of information flow? PPI does not allow us to establish causality. We can establish task-specific changes in connectivity between a seed region and the rest of the brain, however this does not mean that the seed region is the driver rather than the driven area (O'Reilly et al., 2010). In order to determine directionality, one could use dynamic causal modelling (DCM). DCM makes inferences about the coupling amongst brain areas and how these causal influences are modulated by experimental manipulation (Friston, Harrison, & Penny, 2003). For example, Grol and colleagues (2007) used DCM to show that prehension movements strengthen the effective connectivity between occipital, parietal and frontal regions when grasping smaller objects. Moreover, they show that when preparing a grasp, there were differential changes in activity between monkey AIP and PMv and between V6A and PMd when preparing a reach. DCM could be used to analyze the data collected in this study to show that motor areas feed information back to EVC.

We used eccentricity mapping to localize the calcarine sulcus and occipital pole corresponding to the peripheral and foveal cortex, respectively. Though objects were in the visual location corresponding to the periphery, we decoded object orientation in an action-dependent manner in the occipital pole. However, we did not localize V1. To delineate early visual areas (i.e., V1, V2 and V3) standard phase-encoded protocols and retinotopic mapping procedures could be used (DeYoe et al., 1996; Engel, Glover, & Wandell, 1997; Sereno at el., 1995). This would require participants to maintain fixation while viewing 'travelling wave' stimuli consisting of rotating wedges and expanding rings (Arcaro, McMains, Singer, & Kastner, 2009; Arcaro, Pinsk, Li, & Kastner, 2011; Gallivan, Cant, Goodale, & Flanagan, 2014; Swisher et al., 2007). Then one would need to perform cross-correlation analyses to construct phase-encoded retinotopic maps of polar angle and early visual area boundaries (Sereno et al., 1995). Completing retinotopic mapping in addition to eccentricity mapping would allow us to localize action instructions in V1 during planning.

3.3 Remaining Questions

In our study, participants either had to perform Align or Open Hand movements over the object on the left or right. Both target objects were present throughout the whole experiment. Align movements required precise adjustment of the right hand over the objects while Open Hand movements were coarse. We need to ask if orientation of the object is the only feature that played a role in decoding of Location within Action. Since the calcarine sulcus showed a dissociation for both movements, we cannot isolate the object property that is responsible for successful decoding. Both object orientation and location play a role in the dissociation. However, for areas such as the occipital pole, SPOC and pIPS, we showed a significant decoding accuracy for Align only. It is likely that the orientation of the object allows for decoding.

The movements used in this study, Align and Open Hand are not as significantly different from each other compared to grasp and reach or grasp and point. By comparing a grasp to a point, it would allow for the decoding of movement relative to target. However, can we decode different action intentions in the EVC? In our study, we did not show significant decoding accuracies for Action within Location. We would expect significant decoding accuracies for the dissociation of Align versus Open Hand due to the limb-specific representations that arise during the early stages of action planning (Chen et al., 2014; Medendorp et al., 2005; Vesia, Monteon, Sergio, & Crawford, 2006). Since participants only used their right hand to perform actions, we expected to dissociate action type in the object on the left. For example, Gallivan and colleagues (2011) showed that when comparing a grasp versus touch, movements could be successfully decoded in areas such as left SPOC, left mIPS and left aIPS. Moreover, they also decoded upcoming hand actions in the LOC contralaterally (Gallivan et al., 2013). Therefore, a question that remains is whether we can decode the intention of actions to objects in the EVC.

Additionally, we did not record eye movements and must ask if they are responsible for the activity pattern in EVC. Previous univariate and multivariate analyses have been conducted to determine if participants, including naïve ones can fixate for long periods of time. Gallivan and colleagues (2013) showed that when objects are presented in the periphery, participants plan an action towards the object and execute this action, they still maintained fixation. In our study, it is unlikely that participants were moving their eyes to the target object as opposed to fixating during the experiment.

Our study sheds light on the neural mechanism involved in modulating perception by action. We show that actions modulate activity in the EVC through the enhancement of action-relevant features such as orientation. We show feedback connections between EVC and somatomotor areas illustrating the neural mechanism responsible for allowing for successful interaction with the world around us.

3.4 Applications

Studies investigating how our different senses interact during action planning could contribute to the development of devices capable of restoring mobility. In particular, a motivation for this research is to determine the pathways and brain networks involved in turning an intention into an action. In individuals with brain damage, this can help with replacing lost function through the use of different brain regions. For example, this research can be applied to benefit patients with stroke damage. Not only are mortality rates from stroke high, but recurrence after a primary stroke within five years occurs in one third of stroke survivors (Ezeugwu, Garga, & Manns, 2017).

After a stroke, persistent motor deficits are common. It is recommended that these survivors participate in thirty minutes of physical activity per day, however it is problematic to achieve in survivors who have a difficulty even with walking (Furie et al., 2011). Stroke survivors are among the least active of all people with chronic conditions (Sawatzky, Liu-Ambrose, Miller, & Marra, 2007). Compensatory activation has been reported in PMd. Not only is PMd important in movement execution after a stroke (Ward, Don, Furlong, & Lang, 2006), but it is crucial for action planning (Kantak, McGrath, Zahedi, & Luchmee, 2018). Selection of a movement based on visual cues and that require visuomotor transformations engage PMd to a greater extent (Hanakawa, Honda, Zito, Dimyan, & Hallett, 2006). Since PMd plays a role in motor recovery after stroke, our results can help to determine how this is so. Also, connectivity studies help us determine how the motor network communicates. Since we investigated changes in the action network in healthy individuals, our results can be applied to those with motor impairments.

By determining how the action network is affected by stroke, it can improve behavioral interventions aimed at improving arm motor function. Even in individuals deemed as having “good” motor recovery, there is continued difficulty incorporating the affected arm into everyday activities (Stewart & Cramer, 2013). A factor that may be involved in recovery is the engagement of particular brain areas based on the action to be performed. For example, since PMd is a prime candidate for targeted rehabilitation to improve brain circuits and motor function (Stewart, Dewanjee, Shariff, & Cramer, 2016).

This line of research bridges neuroscience with robotics and can contribute to the development of neuroprosthetic devices for patients with movement disorders. Most studies have focused on the motor cortex for obtaining information about movement signals. It provides signals for the movement trajectory of the limbs (Schwartz, 2004; Velliste, Perel, Spalding, Whitford, & Schwartz, 2008). Recently, studies have considered the PPC. Since areas of the PPC are involved in higher-level aspects of action planning, studies have suggested that they can be used to control external devices as part of a brain-machine interface. For example, studies in monkeys that record activity from PPC neurons indicate movement planning in these animals even without execution (Hauschild, Mulliken, Fineman, Loeb, & Andersen, 2012; Musallam, Corneil, Greger, Scherberger, & Andersen, 2004). These results are promising for neuroprosthetics because imagined movements would be an intuitive way of controlling external devices. Aflalo and colleagues (2015) recorded neurons from human PPC in a tetraplegic participant and found that these neurons encode both the goal and trajectory of movements. Moreover, these neurons controlled the goals of a robotic limb and this activity was specific for the imagined effector (right or let limb) (Aflalo et al., 2015). My study illustrates the circuit involved in decoding intention in an action-dependent way. Areas in the PPC were active, even before execution, during the planning phase. These high-level signals from areas involved in planning can be used for neuroprosthetic applications.

3.5 Conclusion

Our results show that the activity pattern of object orientation is modulated in an action-dependent manner. The feedback connections between somatomotor areas and EVC suggest that during action preparation, key features relevant to successful execution of the action are enhanced. This means that the role of the EVC is beyond visual processing and in fact, it may play a role in the visual anticipation of a movement. We see ourselves performing actions everyday hence there are built associations between what we see, feel and do. This information is integrated, not segregated in the brain, likely due to strong connections between vision and somatosensation.

REFERENCES

Aflalo, T., Kellis, S., Klaes, C., Lee, B., Shi, Y., Pejsa, K., … Andersen, R. A. (2015). Decoding motor imagery from the posterior parietal cortex of a tetraplegic human. *Science, 348*(6237), 906–910.

Andersen, R. A., & Buneo, C. A. (2002). Intentional maps in posterior parietal cortex. *Annual Review of Neuroscience*, *25*(1), 189–220.

Andrews, D. P. (1967). Perception of contour orientation in the central fovea. II. Spatial integration. *Vision Research*, *7*(11), 999–1013.

Arcaro, M. J., McMains, S. A., Singer, B. D., & Kastner, S. (2009). Retinotopic organization of human ventral visual cortex. *Journal of Neuroscience, 29*(34), 10638–10652.

Arcaro, M. J., Pinsk, M. A., Li, X., & Kastner, S. (2011). Visuotopic organization of macaque posterior parietal cortex: A functional magnetic resonance imaging study. *Journal of Neuroscience*, *31*(6), 2064–2078.

Baas, J. M. P., Kenemans, J. L., & Mangun, G. R. (2002). Selective attention to spatial frequency: An ERP and source localization analysis. *Clinical Neurophysiology, 113*(11), 1840–1854.

Baldauf, D., & Deubel, H. (2009). Attentional selection of multiple goal positions before rapid hand movement sequences: An event-related potential study. *Journal of Cognitive Neuroscience*, *21*(1), 18–29.

Battaglini, P. P., Muzur, A., Galletti, C., Skrap, M., Brovelli, A., & Fattori, P. (2002). Effects of lesions to area V6A in monkeys. *Experimental Brain Research, 144*(3), 419–422.

Baumann, M. A., Fluet, M. C., & Scherberger, H. (2009). Context-specific grasp movement representation in the macaque anterior intraparietal area. *Journal of Neuroscience*, *29*(20),

6436–6448.

Bekkering, H., & Neggers, S. F. W. (2002). Visual search is modulated by action intentions. *Psychological Science*, *13*(4), 370–374.

Bennett, K. M., & Castiello, U. (1994). Reach to grasp: Changes with age. *Journal of Gerontology*, *49*(1), 1-7.

Beurze, S. M., de Lange, F. P., Toni, I., & Medendorp, W. P. (2009). Spatial and effector processing in the human parietofrontal network for reaches and saccades. *Journal of Neurophysiology*, *101*(6), 3053–3062.

Binkofski, F., Dohle, C., Posse, S., Stephan, K. M., Hefter, H., Seitz, R. J., & Freund, H. J. (1998). Human anterior intraparietal area subserves prehension: A combined lesion and functional MRI activation study. *Neurology*, *50*(5), 1253–1259.

Blohm, G., & Crawford, J. D. (2007). Computations for geometrically accurate visually guided reaching in 3-D space. *Journal of Vision*, *7*(5), 4.

Blohm, G., Keith, G. P., & Crawford, J. D. (2009). Decoding the cortical transformations for visually guided reaching in 3D space. *Cerebral Cortex*, *19*(6), 1372–1393.

Brockway, J. P. (2000). Two functional magnetic resonance imaging f(MRI) tasks that may replace the gold standard, Wada testing, for language lateralization while giving additional localization information. *Brain and Cognition*, *43*(1–3), 57–59.

Buckner, R. L., Bandettini, P. A., O’Craven, K. M., Savoy, R. L., Petersen, S. E., Raichle, M. E., & Rosen, B. R. (1996). Detection of cortical activation during averaged single trials of a cognitive task using functional magnetic resonance imaging. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(25), 14878–14883.

Buckner, R. L., Goodman, J., Burock, M., Rotte, M., Koutstaal, W., Schacter, D., … Dale, A. M.

(1998). Functional-anatomic correlates of object priming in humans revealed by rapid presentation event-related fMRI. *Neuron*, *20*(2), 285–296.

Buxton, R. B., Wong, E. C., & Frank, L. R. (1998). Dynamics of blood flow and oxygenation changes during brain activation: The balloon model. *Magnetic Resonance in Medicine, 39*(6), 855–864.

Cacioppo, J. T., & Decety, J. (2011). Social neuroscience: Challenges and opportunities in the study of complex behavior. *Annals of the New York Academy of Sciences*, *1224*(1), 162–173.

Caminiti, R., Johnson, P. B., Galli, C., Ferraina, S., & Burnod, Y. (1991). Making arm movements within different parts of space: The premotor and motor cortical representation of a coordinate system for reaching to visual targets. *Journal of Neuroscience*, *11*(5), 1182–1197.

Cappadocia, D. C., Monaco, S., Chen, Y., Blohm, G., & Crawford, J. D. (2017). Temporal evolution of target representation, movement direction planning, and reach execution in occipital–parietal–frontal cortex: An fMRI study. *Cerebral Cortex*, (11), 5242–5260.

Carey, D. P., Dijkerman, H. C., Murphy, K. J., Goodale, M. A., & Milner, A. D. (2006). Pointing to places and spaces in a patient with visual form agnosia. *Neuropsychologia*, *44*(9), 1584–1594.

Carrasco, M., & McElree, B. (2001). Covert attention accelerates the rate of visual information processing. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(9), 5363–5367.

Cavina-Pratesi, C., Monaco, S., Fattori, P., Galletti, C., McAdam, T. D., Quinlan, D. J., … Culham, J. C. (2010). Functional magnetic resonance imaging reveals the neural substrates of arm transport and grip formation in reach-to-grasp actions in humans. *Journal of Neuroscience*, *30*(31), 10306–10323.

Chambers, C. D., Allen, C. P. G., Maizey, L., & Williams, M. A. (2013). Is delayed foveal feedback critical for extra-foveal perception? *Cortex*, *49*(1), 327–335.

Chen, Y., Monaco, S., Byrne, P., Yan, X., Henriques, D. Y. P., & Crawford, J. D. (2014). Allocentric versus egocentric representation of remembered reach targets in human cortex. *Journal of Neuroscience*, *34*(37), 12515–12526.

Craighero, L., Fadiga, L., Rizzolatti, G., & Umiltà, C. (1999). Action for perception: A motor-visual attentional effect. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1673–1692.

Crammond, D. J., & Kalaska, J. F. (2000). Prior information in motor and premotor cortex: Activity during the delay period and effect on pre-movement activity. *Journal of Neurophysiology*, *84*(2), 986–1005.

Crawford, J. D., Henriques, D. Y. P., & Medendorp, W. P. (2011). Three-dimensional transformations for goal-directed action. *Annual Review of Neuroscience*, *34*(1), 309–331.

Culham, J. C., Cavina-Pratesi, C., & Singhal, A. (2006). The role of parietal cortex in visuomotor control: What have we learned from neuroimaging? *Neuropsychologia*, *44*(13), 2668–2684.

Culham, J. C., Danckert, S. L., Souza, J. F. X. De, Gati, J. S., Menon, R. S., & Goodale, M. A. (2003). Visually guided grasping produces fMRI activation in dorsal but not ventral stream brain areas. *Experimental Brain Research*, *153*(2), 180–189.

D'Esposito, M., Zarahn, E., & Aguirre, G. K. (1999). Event-related functional MRI: Implications for cognitive psychology. *Psychological Bulletin*, *125*(1), 155–164.

De Valois, R. L., Albrecht, D. G., & Thorell, L. G. (1982). Spatial frequency selectivity of cells in macaque visual cortex. *Vision Research*, *22*(5), 545–559.

Desmurget, M., Jordan, M., Prablanc, C., & Jeannerod, M. (1997). Constrained and unconstrained movements involve different control strategies. *Journal of Neurophysiology*, *77*(3), 1644–1650.

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. *Journal of Neuroscience*, *20*(15), 5835–5840.

DeYoe, E. A., Carman, G. J., Bandettini, P., Glickman, S., Wieser, J., Cox, R., … Neitz, J. (1996). Mapping striate and extrastriate visual areas in human cerebral cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(6), 2382–2386.

Eimer, M., Van Velzen, J., Gherri, E., & Press, C. (2006). Manual response preparation and saccade programming are linked to attention shifts: ERP evidence for covert attentional orienting and spatially specific modulations of visual processing. *Brain Research*, *1105*(1), 7–19.

Engel, S. A., Glover, G. H., & Wandell, B. A. (1997). Retinotopic organization in human visual cortex and the spatial precision of functional MRI. *Cerebral Cortex*, *7*(2), 181–192.

Eskandar, E. N., & Assad, J. A. (1999). Dissociation of visual, motor and predictive signals in parietal cortex during visual guidance. *Nature Neuroscience*, *2*(1), 88–93.

Ezeugwu, V. E., Garga, N., & Manns, P. J. (2017). Reducing sedentary behaviour after stroke: Perspectives of ambulatory individuals with stroke. *Disability and Rehabilitation*, *39*(25), 2551–2558.

Fagg, A. H., & Arbib, M. A. (1998). Modeling parietal-premotor interactions in primate control of grasping. *Neural Networks*, *11*(7–8), 1277–1303.

Fagioli, S., Hommel, B., & Schubotz, R. I. (2007). Intentional control of attention: Action planning primes action-related stimulus dimensions. *Psychological Research*, *71*(1), 22–29.

Fattori, P., Gamberini, M., Kutz, D. F., & Galletti, C. (2001). “Arm-reaching” neurons in the parietal area V6A of the macaque monkey. *European Journal of Neuroscience*, *13*(12), 2309–2313.

Fattori, P., Raos, V., Breveglieri, R., Bosco, A., Marzocchi, N., & Galletti, C. (2010). The dorsomedial pathway is not just for reaching: Grasping neurons in the medial parieto-occipital cortex of the macaque monkey. *Journal of Neuroscience*, *30*(1), 342–349.

Faugier-Grimaud, S., Frenois, C., & Peronnet, F. (1985). Effects of posterior parietal lesions on visually guided movements in monkeys. *Experimental Brain Research*, *59*(1), 125–138.

Faugier-Grimaud, S., Frenois, C., & Stein, D. G. (1978). Effects of posterior parietal lesions on visually guided behavior in monkeys. *Neuropsychologia*, *16*(2), 151–168.

Fernandez-Ruiz, J., Goltz, H. C., DeSouza, J. F. X., 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. *Cerebral Cortex*, *17*(10), 2283–2292.

Filimon, F. (2010). Human cortical control of hand movements: Parietofrontal networks for reaching, grasping, and pointing. *The Neuroscientist*, *16*(4), 388–407.

Filimon, F., Nelson, J. D., Huang, R.-S., & Sereno, M. I. (2009). Multiple parietal reach regions in humans: Cortical representations for visual and proprioceptive feedback during on-line reaching. *Journal of Neuroscience*, *29*(9), 2961–2971.

Friston, K. ., Buechel, C., Fink, G., Morris, J., Rolls, E., & Dolan, R. (1997). Psychophysiological and modulatory interactions in neuroimaging. *NeuroImage*, *6*(3), 218–

229.

Friston, K. J. (2011). Functional and effective connectivity: A review. *Brain Connectivity*, *1*(1), 13–36.

Friston, K. J., Frith, C. D., Frackowiak, R. S., & Turner, R. (1995). Characterizing dynamic brain responses with fMRI: A multivariate approach. *NeuroImage*, *2*(2), 166–172.

Friston, K. J., Harrison, L., & Penny, W. (2003). Dynamic causal modelling. *NeuroImage*, *19*(4), 1273–302.

Friston, K. J., Holmes, A. P., Price, C. J., Büchel, C., & Worsley, K. J. (1999). Multisubject fMRI studies and conjunction analyses. *NeuroImage*, *10*(4), 385–396.

Furie, K. L., Kasner, S. E., Adams, R. J., Albers, G. W., Bush, R. L., Fagan, S. C., … Wentworth, D. (2011). Guidelines for the prevention of stroke in patients with stroke or transient ischemic attack: A guideline for healthcare professionals from the American Heart Association/American Stroke Association. *Stroke*, *42*(1), 227–276.

Galletti, C., Fattori, P., Kutz, D. F., & Battaglini, P. P. (1997). Arm movements-related neurons in the visual area V6A of the macaque superior parietal lobule. *European Journal of Neuroscience*, *9*, 410–413.

Gallivan, J. P., Cant, J. S., Goodale, M. A., & Flanagan, J. R. (2014). Representation of object weight in human ventral visual cortex. *Current Biology*, *24*(16), 1866–1873.

Gallivan, J. P., Chapman, C. S., Mclean, D. A., Flanagan, J. R., & Culham, J. C. (2013). Activity patterns in the category-selective occipitotemporal cortex predict upcoming motor actions. *European Journal of Neuroscience*, *38*(3), 2408–2424.

Gallivan, J. P., & Culham, J. C. (2015). Neural coding within human brain areas involved in actions. *Current Opinion in Neurobiology*, *33*, 141–149.

Gallivan, J. P., McLean, D. A., Flanagan, J. R., & Culham, J. C. (2013). Where one hand meets the other: Limb-specific and action-dependent movement plans decoded from preparatory signals in single human frontoparietal brain areas. *Journal of Neuroscience*, *33*(5), 1991–2008.

Gallivan, J. P., McLean, D. A., Smith, F. W., & Culham, J. C. (2011). Decoding effector-dependent and effector-independent movement intentions from human parieto-frontal brain activity. *Journal of Neuroscience*, *31*(47), 17149–17168.

Ganel, T., & Goodale, M. A. (2017). Still holding after all these years: An action-perception dissociation in patient DF. *Neuropsychologia*, (17), 1–6.

Gentilucci, M., Castiello, U., Corradini, M. L., Scarpa, M., Umiltà, C., & Rizzolatti, G. (1991). Influence of different types of grasping on the transport component of prehension movements. *Neuropsychologia*, *29*(5), 361–378.

Goodale, M. A, Jakobson, L. S, & Keilor, J. M. (1994). Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia*, *32*(10), 1159–1178.

Goodale, M. A., Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences*, *15*(1), 20–25.

Goodale, M. A., Westwood, D. A., & Milner, A. D. (2004). Two distinct modes of control for object-directed action. *Progress in Brain Research*, *144*, 131–44.

Grafton, S. T., Fagg, A. H., Woods, R. P., & Arbib, M. A. (1996). Functional anatomy of pointing and grasping in humans. *Cerebral Cortex*, *6*(2), 226–237.

Grefkes, C., Ritzl, A., Zilles, K., & Fink, G. R. (2004). Human medial intraparietal cortex subserves visuomotor coordinate transformation. *NeuroImage*, *23*(4), 1494–1506.

Grol, M. J., Majdandzic, J., Stephan, K. E., Verhagen, L., Dijkerman, H. C., Bekkering, H., …

Toni, I. (2007). Parieto-frontal connectivity during visually guided grasping. *Journal of Neuroscience*, *27*(44), 11877–11887.

Gutteling, T. P., Kenemans, J. L., & Neggers, S. F. W. (2011). Grasping preparation enhances orientation change detection. *PLoS ONE*, *6*(3), e17675.

Gutteling, T. P., Park, S. Y., Kenemans, J. L., Neggers, S. F. W., Dettmers, C., Weiller, C., & Büchel, C. (2013). TMS of the anterior intraparietal area selectively modulates orientation change detection during action preparation. *Journal of Neurophysiology*, *110*(1), 33–41.

Gutteling, T. P., Petridou, N., Dumoulin, S. O., Harvey, B. M., Aarnoutse, E. J., Kenemans, J. L., & Neggers, S. F. W. (2015). Action preparation shapes processing in early visual cortex. *Journal of Neuroscience*, *35*(16), 6472–6480.

Hanakawa, T., Honda, M., Zito, G., Dimyan, M. A., & Hallett, M. (2006). Brain activity during visuomotor behavior triggered by arbitrary and spatially constrained cues: An fMRI study in humans. *Experimental Brain Research*, *172*(2), 275–282.

Hannus, A., Cornelissen, F. W., Lindemann, O., & Bekkering, H. (2005). Selection-for-action in visual search. *Acta Psychologica*, *118*(1–2), 171–191.

Harrison, S. A., & Tong, F. (2009). Decoding reveals the contents of visual working memory in early visual areas. *Nature*, *458*(7238), 632–635.

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. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(42), 17075–17080.

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 inventral temporal cortex.

Science, *293*(5539), 2425–2430.

Hendrix, C. M., Mason, C. R., & Ebner, T. J. (2009). Signaling of grasp dimension and grasp force in dorsal premotor cortex and primary motor cortex neurons during reach to grasp in the monkey. *Journal of Neurophysiology*, *102*(1), 132–145.

Hillyard, S. A., & Anllo-Vento, L. (1998). Event-related brain potentials in the study of visual selective attention. *Proceedings of the National Academy of Sciences of the United States of America*, *95*(3), 781–787.

Hogan, N., & Flash, T. (1987). Moving gracefully: Quantitative theories of motor coordination. *Trends in Neurosciences*, *10*(4), 170–174.

Hubel, D. H., & Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *The Journal of Physiology*, *195*(1), 215–243.

Hubel, D. H., & Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat’s visual cortex. *The Journal of Physiology*, *160*, 106–154.

Iacoboni, M. (2006). Visuo-motor integration and control in the human posterior parietal cortex: Evidence from TMS and fMRI. *Neuropsychologia*, *44*(13), 2691–2699.

Jakobson, L. S., Archibald, Y. M., Carey, D. P., & Goodale, M. A. (1991). A kinematic analysis of reaching and grasping movements in a patient recovering from optic ataxia. *Neuropsychologia*, *29*(8), 803–809.

Jeannerod, M. (1984). The timing of natural prehension movements. *Journal of Motor Behavior*, *16*(3), 235–254.

Jeannerod, M. (1986). Models for the programming of goal-directed movements (or how to get things less complex). *Archives Internationales de Physiologie et de Biochimie*, *94*(4), 63-76.

Jeannerod, M. (1999). The 25th Bartlett Lecture: To act or not to act: Perspectives on the representation of actions. *The Quarterly Journal of Experimental Psychology Section A, Human Experimental Psychology*, *52*(1), 1–29.

Jeannerod, M., Arbib, M. A., Rizzolatti, G., & Sakata, H. (1995). Grasping objects: The cortical mechanisms of visuomotor transformation. *Trends in Neurosciences*, *18*(7), 314–320.

Kamitani, Y., & Tong, F. (2005). Decoding the visual and subjective contents of the human brain. *Nature Neuroscience*, *8*(5), 679–685.

Kantak, S., McGrath, R., Zahedi, N., & Luchmee, D. (2018). Behavioral and neurophysiological mechanisms underlying motor skill learning in patients with post-stroke hemiparesis. *Clinical Neurophysiology*, *129*(1), 1–12.

Karnath, H. O., & Perenin, M. T. (2005). Cortical control of visually guided reaching: Evidence from patients with optic ataxia. *Cerebral Cortex*, *15*(10), 1561–1569.

Karnath, H. O., & Rorden, C. (2012). The anatomy of spatial neglect. *Neuropsychologia*, *50*(6), 1010–1017.

Kriegeskorte, N., & Bandettini, P. (2007). Analyzing for information, not activation, to exploit high-resolution fMRI. *NeuroImage*, *38*(4), 649–662.

Kriegeskorte, N., Goebel, R., & Bandettini, P. (2006). Information-based functional brain mapping. *Proceedings of the National Academy of Sciences*, *103*(10), 3863–3868.

Króliczak, G., McAdam, T. D., Quinlan, D. J., & Culham, J. C. (2008). The human dorsal stream adapts to real actions and 3D shape processing: A functional magnetic resonance imaging study. *Journal of Neurophysiology*, *100*(5), 2627–2639.

McLaren, D. G., Ries, M. L., Xu, G., & Johnson, S. C. (2012). A generalized form of context-dependent psychophysiological interactions (gPPI): A comparison to standard approaches. *NeuroImage*, *61*(4), 1277–1286.

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. *Journal of Neurophysiology*, *93*(2), 954–962.

Medendorp, W. P., Goltz, H. C., Vilis, T., & Crawford, J. D. (2003). Gaze-centered updating of visual space in human parietal cortex. *Journal of Neuroscience*, *23*(15), 6209–6214.

Medendorp, W. P., Tweed, D. B., & Crawford, J. D. (2003). Motion parallax is computed in the updating of human spatial memory. *Journal of Neuroscience*, *23*(22), 8135–8142.

Mevorach, C., Hodsoll, J., Allen, H., Shalev, L., & Humphreys, G. (2010). Ignoring the elephant in the room: A neural circuit to downregulate salience. *Journal of Neuroscience, 30*(17), 6072–6079.

Mevorach, C., Humphreys, G. W., & Shalev, L. (2009). Reflexive and preparatory selection and suppression of salient information in the right and left posterior parietal cortex. *Journal of Cognitive Neuroscience, 21*(6), 1204–1214.

Mevorach, C., Shalev, L., Allen, H. A., & Humphreys, G. W. (2009). The left intraparietal sulcus modulates the selection of low salient stimuli. *Journal of Cognitive Neuroscience*, *21*(2), 303–315.

Milner, A. D., & Goodale, M. A. (2008). Two visual systems re-viewed. *Neuropsychologia*, *46*(3), 774–785.

Monaco, S., Buckingham, G., Sperandio, I., & Crawford, J. D. (2016). Editorial: Perceiving and acting in the real world: From neural activity to behavior. *Frontiers in Human Neuroscience*, *10*, 179.

Monaco, S., Cavina-Pratesi, C., Sedda, A., Fattori, P., Galletti, C., & Culham, J. C. (2011). Functional magnetic resonance adaptation reveals the involvement of the dorsomedial stream in hand orientation for grasping. *Journal of Neurophysiology, 106*(5), 2248–2263.

Monaco, S., Gallivan, J. P., Figley, T. D., Singhal, A., & Culham, J. C. (2017). Recruitment of foveal retinotopic cortex during haptic exploration of shapes and actions in the dark. *Journal of Neuroscience*, 2428–2416.

Moore, T., & Fallah, M. (2004). Microstimulation of the frontal eye field and its effects on covert spatial attention. *Journal of neurophysiology, 91*(1), 152–162.

Morasso, P. (1981). Spatial control of arm movements. *Experimental Brain Research*, *42*(2), 223–227.

Murata, A., Fadiga, L., Fogassi, L., Gallese, V., Raos, V., Rizzolatti, G., … Cohen, L. G. (2014). Object representation in the ventral premotor cortex (Area F5) of the monkey object representation in the ventral premotor cortex (Area F5) of the monkey. *Journal of Neurophysiology*, 2226–2230.

Murata, A., Gallese, V., Luppino, G., Kaseda, M., & Sakata, H. (2000). Selectivity for the shape, size, and orientation of objects for grasping in neurons of monkey parietal area AIP. *Journal of Neurophysiology*, *83*, 2580–2601.

Musallam, S., Corneil, B. D., Greger, B., Scherberger, H., & Andersen, R. A. (2004). Cognitive control signals for neural prosthetics. *Science*, *305*(5681), 258–262.

Norman, K. A., Polyn, S. M., Detre, G. J., & Haxby, J. V. (2006). Beyond mind-reading: Multi-voxel pattern analysis of fMRI data. *Trends in Cognitive Sciences*, *10*(9), 424–430.

O’Reilly, J. X., Woolrich, M. W., Behrens, T. E. J., Smith, S. M., & Johansen-Berg, H. (2012). Tools of the trade: Psychophysiological interactions and functional connectivity. *Social Cognitive and Affective Neuroscience, 7*(5), 604–609.

Ogawa, S., Tank, D. W., Menon, R., Ellermann, J. M., Kim, S. G., Merkle, H., & Ugurbil, K.

(1992). Intrinsic signal changes accompanying sensory stimulation: Functional brain mapping with magnetic resonance imaging. *Proceedings of the National Academy of Sciences of the United States of America*, *89*(13), 5951–5955.

Perry, C. J., Sergio, L. E., Crawford, J. D., & Fallah, M. (2015). Hand placement near the visual stimulus improves orientation selectivity in V2 neurons. *Journal of Neurophysiology*, *113*(7), 2859–2870.

Praamstra, P., Boutsen, L., & Humphreys, G. W. (2005). Frontoparietal control of spatial attention and motor intention in human EEG. *Journal of Neurophysiology*, *94*(1), 764–774.

Raos, V. (2005). Functional properties of grasping-related neurons in the ventral premotor area F5 of the Macaque Monkey. *Journal of Neurophysiology*, *95*(2), 709–729.

Rizzolatti, G., Camarda, R., Fogassi, L., Gentilucci, M., Luppino, G., & Matelli, M. (1988). Functional organization of inferior area 6 in the macaque monkey. II. Area F5 and the control of distal movements. *Experimental Brain Research, 71*(3), 491–507.

Rizzolatti, G., Fogassi, L., & Gallese, V. (1997). Parietal cortex: From sight to action. *Current Opinion in Neurobiology*, *7*(4), 562–567.

Rizzolatti, G., Riggio, L., Dascola, I., & Umilta, C. (1987) Reorienting attention across the horizontal and vertical meridians: Evidence in favor of pre-motor theory of attention. *Neuropsychologia*, *25*, 31–40.

Rombouts, S. A., Barkhof, F., Hoogenraad, F. G., Sprenger, M., Valk, J., & Scheltens, P. (1997). Test-retest analysis with functional MR of the activated area in the human visual cortex. *American Journal of Neuroradiology*, *18*(7), 1317–1322.

Ruff, C. C., Bestmann, S., Blankenburg, F., Bjoertomt, O., Josephs, O., Weiskopf, N., … Driver, J. (2008). Distinct causal influences of parietal versus frontal areas on human visual cortex:

Evidence from concurrent TMS-fMRI. *Cerebral Cortex*, *18*(4), 817–827.

Ruff, C. C., Blankenburg, F., Bjoertomt, O., Bestmann, S., Freeman, E., Haynes, J. D., … Driver, J. (2006). Concurrent TMS-fMRI and psychophysics reveal frontal influences on human retinotopic visual cortex. *Current Biology, 16*(15), 1479–1488.

Sakata, H., Taira, M., Kusunoki, M., Murata, A., Tanaka, Y., & Tsutsui, K. (1998). Neural coding of 3D features of objects for hand action in the parietal cortex of the monkey. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *353*(1373), 1363–1373.

Sawatzky, R., Liu-Ambrose, T., Miller, W. C., & Marra, C. A. (2007). Physical activity as a mediator of the impact of chronic conditions on quality of life in older adults. *Health and Quality of Life Outcomes*, *5*(1), 68.

Schacter, D. L., Buckner, R. L., Koutstaal, W., Dale, A. M., & Rosen, B. R. (1997). Late onset of anterior prefrontal activity during true and false recognition: An event-related fMRI study. *NeuroImage*, *6*(4), 259–269.

Schira, M. M., Tyler, C. W., Breakspear, M., & Spehar, B. (2009). The foveal confluence in human visual cortex. *Journal of Neuroscience*, *29*(28), 9050–9058.

Schwartz, A. B. (2004). Cortical neural prosthetics. *Annual Review of Neuroscience*, *27*(1), 487–507.

Sereno, M. I., Dale, A. M., Reppas, J. B., Kwong, K. K., Belliveau, J. W., Brady, T. J. (1995). Borders of multiple visual areas in humans revealed by functional magnetic resonance imaging. *Science, 5212*, 2–7.

Silvanto, J., Muggleton, N., Lavie, N., & Walsh, V. (2009). The perceptual and functional consequences of parietal top-down modulation on the visual cortex. *Cerebral Cortex*, *19*(2),

327–330.

Singhal, A., Monaco, S., Kaufman, L. D., & Culham, J. C. (2013). Human fMRI reveals that delayed action re-recruits visual perception. *PLoS ONE*, *8*(9).

Slagter, H. A., Kok, A., Mol, N., & Kenemans, J. L. (2005). Spatio-temporal dynamics of top-down control: Directing attention to location and/or color as revealed by ERPs and source modeling. *Cognitive Brain Research*, *22*(3), 333–348.

Stewart, J. C., & Cramer, S. C. (2013). Patient-reported measures provide unique insights into motor function after stroke. *Stroke*, *44*(7), e80.

Stewart, J. C., Dewanjee, P., Shariff, U., & Cramer, S. C. (2016). Dorsal premotor activity and connectivity relate to action selection performance after stroke. *Human Brain Mapping*, *37*(5), 1816–1830.

Strasburger, H., Rentschler, I., & Juttner, M. (2011). Peripheral vision and pattern recognition: A review. *Journal of Vision*, *11*(5), 13.

Swisher, J. D., Halko, M. A., Merabet, L. B., McMains, S. A., & Somers, D. C. (2007). Visual topography of human intraparietal sulcus. *Journal of Neuroscience*, *27*(20), 5326–5337.

Taira, M., Mine, S., Georgopoulos, A. P., Murata, A., & Sakata, H. (1990). Parietal cortex neurons of the monkey related to the visual guidance of hand movement. *Experimental Brain Research*, *83*(1), 29–36.

Tal, Z., Geva, R., & Amedi, A. (2016). The origins of metamodality in visual object area LO: Bodily topographical biases and increased functional connectivity to S1. *NeuroImage*, *127*, 363–375.

Tosoni, A., Galati, G., Romani, G. L., & Corbetta, M. (2008). Sensory-motor mechanisms in human parietal cortex underlie arbitrary visual decisions. *Nature Neuroscience*, *11*(12),

1446–1453.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.

Tunik, E., Frey, S. H., & Grafton, S. T. (2005). Virtual lesions of the anterior intraparietal area disrupt goal-dependent on-line adjustments of grasp. *Nature Neuroscience, 8*(4), 505.

Valyear, K. F., Culham, J. C., Sharif, N., Westwood, D., & Goodale, M. A. (2006). A double dissociation between sensitivity to changes in object identity and object orientation in the ventral and dorsal visual streams: A human fMRI study. *Neuropsychologia*, *44*(2), 218–228.

van Elk, M., van Schie, H. T., Neggers, S. F. W., Bekkering, H., & Sakata, H. (2010). Neural and temporal dynamics underlying visual selection for action. *Journal of Neurophysiology*, *104*(2), 972–983.

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.

Verhagen, L., Dijkerman, H. C., Grol, M. J., & Toni, I. (2008). Perceptuo-motor interactions during prehension movements. *Journal of Neuroscience*, *28*(18), 4726–4735.

Vesia, M., & Crawford, J. D. (2012). Specialization of reach function in human posterior parietal cortex. *Experimental Brain Research*, *221*(1), 1–18.

Vesia, M., Monteon, J. A., Sergio, L. E., & Crawford, J. D. (2006). Hemispheric asymmetry in memory-guided pointing during single-pulse transcranial magnetic stimulation of human parietal cortex. *Journal of Neurophysiology*, *96*(6), 3016–3027.

Vesia, M., Prime, S. L., Yan, X., Sergio, L. E., & Crawford, J. D. (2010). Specificity of human parietal saccade and reach regions during transcranial magnetic stimulation. *Journal of Neuroscience, 30*(39), 13053–13065.

Wandell, B. A. (1995). Useful quantities in Vision Science, Inner cover pages in “Foundation of vision.” Sunderland, MA: Sinauer Associates.

Wandell, B. A., Dumoulin, S. O., & Brewer, A. A. (2007). Visual feld maps in human cortex. *Neuron*, *56*(2), 366–383.

Ward, R. P., Don, C. W., Furlong, K. T., & Lang, R. M. (2006). Predictors of long-term mortality in patients with ischemic stroke referred for transesophageal echocardiography. *Stroke*, *37*(1), 204–208.

Westendorff, S., Klaes, C., & Gail, A. (2010). The cortical timeline for deciding on reach motor goals. *Journal of Neuroscience*, *30*(15), 5426–5436.

Westheimer, G., Shimamura, K., & McKee, S. P. (1976). Interference with line-orientation sensitivity. *Journal of the Optical Society of America*, *66*(4), 332–338.

Williams, M. A., Baker, C. I., Op De Beeck, H. P., Mok Shim, W., Dang, S., Triantafyllou, C., & Kanwisher, N. (2008). Feedback of visual object information to foveal retinotopic cortex. *Nature Neuroscience*, *11*(12), 1439–1445.

APPENDICES

Appendix A: Author Contributions

I contributed to the project design, data analysis, data interpretation and I wrote the paper. Dr. Crawford contributed to data interpretation and editorial comments. Dr. Monaco contributed to project design, data collection, data interpretation and provided editorial comments.