CONGRUENCY OF EYE MOVEMENT METRICS ACROSS MOTOR SIMULATION STATES: IMPLICATIONS FOR MOTOR (RE)LEARNING

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Abstract

This thesis contains a series of studies that report, for the first time, the congruence between physical, imagined and observed movement though a range of eye movement markers as a test of Jeannerod's Simulation Theory (Jeannerod, 1994, 2001). First, the eye gaze metrics of healthy young individuals across all the action-related processes in a single paradigm is reported. The finding from this study suggested a temporal and spatial similarity between action execution (AE) and action observation (AO), and a spatial similarity between AE and motor imagery (MI). These findings suggest that AO could be used to simulate actions that involve a critical temporal element. Second, the influence of early ageing on gaze metrics was examined. The findings from this study indicated that whilst the profile of metrics for AE showed age-related decline, it was less evident in AO and MI although there was evidence of some age-related decline across all the three processes. Third, the influence of visual perspective on eye movements during movement simulation is reported. The data analysis in this study was novel and allowed, for the first time, eye gaze to be used to quantify MI and highlighted the importance of social gaze in AO and its absence in MI. Taken together, the finding that some eye metrics are preserved in more covert behaviours provides support for the efficacy of (re)learning optimal eye gaze strategies through AO- and MI-supported movement-based interventions for older adults with movement dysfunction. Therefore, in the final study, the development of a fully-integrated AE-AO-MI toolkit is reported. A new, App-based approach to the integration of movement simulation in rehabilitation is described in detail.

Twenty years after he first proposed his Simulation Theory of MI the novel findings from this programme of work provide substantial support for the concept. This thesis highlights the advantage of using advanced eye gaze technology as an important marker to inform the on-going debate on the extent of the neural substrate sharedness as the central tenet to Simulation Theory. The findings of the studies will make an important impact on the use of simulation procedures for motor relearning.

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List of abbreviations used throughout the thesis

ADL – Activity of Daily Living

AE – Action Execution

AO – Action Observation

ARAT – Action Research Arm Test

AST - Action Simulation Training

BBT – Block and Box Test

BOLD – Blood Oxygen Level Dependent

EHI – Edinburgh Handedness Inventory

EMG – Electromyography

fMRI- Functional Magnetic Resonance Imaging

GMI – Guided Motor Imagery

hMNS – Human Mirror Neuron System

ID – Index of Difficulty

MEG – Magnetoencephalography

MI – Motor Imagery

MIQ-RS – Movement Imagery Questionnaire Revised Second Version

NHS – National Health Service

px – Pixel

RCT – Randomised Control Trial

ROI – Region Of Interest

SMA – Supplementary Motor Area

UCD - User Centred Design

UGMI – Unguided Motor Imagery

VI – Visual Imagery

VFT – Virtual Fitts' Task

VMIQ-2 – Vividness of Movement Imagery Questionnaire – 2

1PP - First Person Perspective

3PP – Third Person Perspective

1 Introduction

The use of psychological interventions for learning new motor skills is not new. Parents of young children have used demonstrations and guiding cues to help their offspring's skill development since humans first used tools in a meaningful way. Later, the child uses the motor representational memories of the demonstration event to facilitate their movement patterns by attempting to match those of their parents. This example of the role of covert behaviour in motor skill acquisition has been essential for human development (Berger, Carli, Hammersla, Karshmer, & Sanchez, 1979; Magill, 2000). More recently, sports performers and clinicians, guided by the evidence-based findings that covert mental training techniques have motor learning efficacy, have aimed to exploit the same mechanisms (Ertelt et al., 2007; Smith, Wright, & Cantwell, 2008). By their very nature, however, action execution (AE), action observation (AO) and motor imagery (MI) are quite different processes and it is too simplistic to assume that they are just variants of a single 'motor programme'. Many factors contribute to the effectiveness of AO and MI (e.g., visual perspective and movement agency) and these will be discussed in detail throughout each of the studies in this thesis. More importantly, the way each of the factors can be controlled to optimise the outcome of the intervention was essential to the design of the studies.

The most important tenet across all studies, however, was the consideration of eye gaze metrics. If, as Vickers (1996) has argued, an individual's eye fixations tell us something about their attentional allocation and if visual attention is important for motoric understanding (Bandura, 1986) then it follows that eye gaze characteristics must be equally important in covert techniques that attest to be valid motor learning interventions. To date, there has been no published research that has considered the role and congruence of eye movement metrics across both covert and overt conditions.

The work reported in this thesis aimed to further our knowledge of the role of MI and AO processes within healthy and clinical populations by considering some of the detailed kinematics of eye movements as individuals observe and imagine movements. The work draws on the motor cognition literature from across a range of disciplines to more fully understand the role of eye gaze within the covert techniques. There is extensive literature in the sports domain and many of the variables that influence the effectiveness of MI and AO, or observational learning, have been investigated (e.g., for MI see Smith et al., 2008; and for observational learning see Williams, Ward, & Chapman, 2003). Sport psychology theories and models have informed the work in this thesis directly. In addition, the cognitive neuroscience, motor learning, and clinical rehabilitation literature has also been considered. In the case of the latter there has been more of a concern since the literature tends to suggest a more varied and limited consideration of the important factors known to influence MI, with few reporting any control of the recognised factors underpinning MI quality and effectiveness. The studies reported in this thesis have addressed the identified methodological limitations in the clinical rehabilitation and MI work. In addition, across all the psychological skills training literature, there has been almost no recognition that eye gaze may be fundamentally important to the delivery of these techniques. This thesis aimed to address these significant gaps in the literature and was guided by a theoretical approach to motor cognition that has had a significant impact on research in this area since it was first reported in 1994. Jeannerod's seminal paper '*The representing brain: neural correlates of motor intention and imagery'* published in *Behavioral Brain Sciences* (Jeannerod, 1994) was the first to suggest a mechanism for how the brain, and particularly the motor areas, may share neural substrate across different movement-related behaviours. Jeannerod's Simulation Theory (Jeannerod, 2001) and its central tenets were fundamental to all the study designs reported in this thesis.

The Simulation Theory posits the existence of a common neural substrate that is activated during AE, AO, and MI. Drawing largely on evidence from behavioural and cognitive psychology, psychophysiology, and cognitive neuroscience, the theory was the first to combine three processes that had historically been examined independently. When first presented, the theory may have seemed ambitious; why should three distinctly different processes be interdependent? The introductory section addresses this question and discusses the evolution of Jeannerod's Simulation Theory.

1.1 Action observation

Demonstrations are used ubiquitously to learn novel movements or improve motor skills (Magill, 2000). From as early as a few hours old, humans begin to learn and understand motor behaviour through the AO of others (Meltzoff & Moore, 1983). As discussed above, this covert process is suggested to be of major evolutionary benefit, underpinning not only motor learning (Berger et al., 1979) but also other sophisticated mental functions such as communication (Rizzolatti & Arbib, 1998) and socialisation (Gallese & Goldman, 1998). Action demonstrations can modify behaviour by various processes. For example, an individual may adapt his or her behaviour to match a model (Heyes, 2001; Prinz, 1987), an object (emulation: Heyes, 2001) or a perceived goal or outcome (Byrne & Russon, 1998). In the skill acquisition/motor learning literature AO is seen as more pertinent. AO can be defined as the process by which an individual observes behaviour and adapts his/her action(s) accordingly (Bandura, 1986).

1.1.1 Theories of action observation

The Social Cognitive Theory (Bandura, 1986) suggests that AO leads to motor learning through an informative feedback function. The AO process allows individuals to acquire movement patterns in the absence of the costly ‘trial and error’ approach that accompanies physical practice. The process comprises four inter-related sub-processes: attention; retention; motor reproduction; and motivation. Attention refers to how a learner selectively attends to, and extracts, distinctive features of the modelled action. This process may be modified by the learner’s perceptions, past experiences, and current situational requirements. During retention the observed action is stored in memory by reconstructing and transforming it using strategies such as labelling, coding, and images. Motor reproduction involves the symbolic representation of the memorised action that is used to guide overt performance, and motivation affects performance by motivating the individual to execute the modelled response. Of these four inter-related processes, the role of attention is particularly pertinent to this thesis. If visual percepts are memorised for later recall during motor production, then ensuring that all key visual information is initially acquired may be critical to the motor learning outcome.

The idea of a representation guiding motor planning and performance is retained in more recent theories such as the Common Coding Theory (Prinz, 1997, see Figure 1.1) and the Direct Matching Hypothesis (Rizzolatti, Fogassi, & Gallese, 2001).

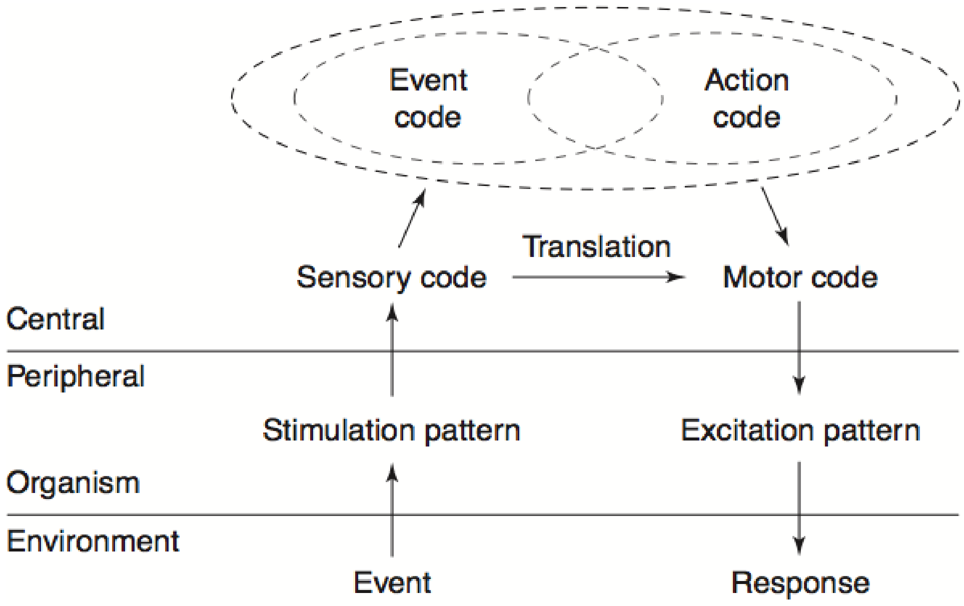


Figure 1-1: Major functional components suggested to underlie perception and action control in the Common Coding Theory (Prinz, 1997).

In these theories the representation is linked to the neural mechanisms specific to action planning and comprises two parts: (i) a representation of the body as a force generator; and, (ii) a representation of the goal of the action encoded in a pragmatic code (Decety & Grèzes, 1999). The Common Coding Theory contends that a common representation exists between the late products of perception, referred to as event codes, and the early antecedents of action, referred to as action codes. The event codes are generated by the stimulation of sense organs in response to the environment, whereas the overlapping action codes generate motor excitability in the muscles. In this context, (re)motor learning (which may involve the learning of novel movements or the relearning of inefficient movements) in AO would be achieved through the manipulation of the common representation via perception. Conceived at a time when functional magnetic resonance imaging (fMRI) equipment was still in its infancy, the theory was based largely on the behavioural findings of studies using inductive and interference paradigms to study action performance. These studies demonstrated that concurrent AE and AO of similar actions led to action induction or enhancement (inductive paradigm), whereas the concurrent AE and AO of dissimilar events led to action impairment (interference paradigm).

The advent of widely available brain imaging equipment has permitted cognitive neuroscientists to examine the neural architecture underlying AE and AO. Based on evidence from this alternative methodological approach, and championing the idea of a common representation between AE and AO, the Direct Matching Hypothesis (Rizzolatti et al., 2001) was developed. The determination of the common neural network underpinning this theory stemmed from the discovery of a particular subset of visuomotor neurons in the pre-motor cortex of macaque monkeys (Rizzolatti et al., 1988). These neurons, referred to as ‘mirror neurons’, were found to discharge when the macaque either observed or performed a goal-directed motor act (Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; for a comprehensive review see Hickok, 2009). Using fMRI, Iacoboni et al. (1999) highlighted their anatomical location in humans and stated that they were homologous to those of the macaque. The Direct Matching Hypothesis contends that observed actions are understood (i.e., internally described) because neurons that fire in the perceptual system are propagated to motor areas where additional information about the action is provided. In this regard, an ‘intrapersonal resonance’ is suggested to occur between the motor and perceptual systems (Uithol, van Rooij, Bekkering, & Haselager, 2011). The human mirror neuron system (hMNS) describes the subset of neurons activated during this process, and the term ‘motor resonance’ has become common to describe the phenomenon (Rizzolatti et al., 2001).

The congruency of the observer’s motor representation with the observed action is dependent upon the observer’s motor skill. For example, the movements of an expert performer will not be held in the motor repertoire of a novice performer and thus, simplistically, the motor resonance experienced by a novice observing an expert may be less than that experienced by an expert observing an expert (Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006). The motor representation is highly plastic and it is this feature that can be exploited when learning through AO; repeated AO, in conjunction with or without AE, is reported to alter the neural activation pattern and support motor learning (Ertelt et al., 2007). Indeed, studies have shown that increasing the speed of a movement during AO biases the subsequent AE of the same action (Bienkiewicz, Rodger, Young, & Craig, 2013). If the motor representation can be manipulated through visual perception, it follows that undesirable or sub-optimal manipulation may also occur if inappropriate visual information is acquired through an ineffective gaze strategy. This suggestion echoes a core contention of Social Cognitive Theory that an individual will not learn effectively from AO unless he or she attends to, and accurately perceives, the relevant aspects of the modelled action. These ideas form the main focus of this thesis.

1.2 Imagery

Another technique suggested to activate mental representations to improve performance is mental imagery. Mental imagery is a process by which information is represented in the brain in the absence of appropriate sensory input (Moran, 2009). As a construct, imagery is multi-sensory and multi-modal; the sight, feel, smell, taste, and sound of an imagined event may be simulated during the process. Historically, the majority of research conducted by cognitive psychologists has focussed on the visual modality. Increasingly MI, defined as the conscious representation of action in the absence of movement execution (Jeannerod & Frak, 1999), is being examined by cognitive psychologists and neuroscientists. In the literature the distinction between these two types of imagery (visual and motor) is often unclear (Morris, Spittle, & Watt, 2005). This thesis adopts the view that human movement can be imagined using visual imagery (VI) and MI, but kinaesthesis (the physiological feeling that accompanies movement) can only developed during MI. MI has many parallels with AO: (i) it may be used to influence motor processes, such as the kinematics, kinetics, and co-ordination of action, and cognitive process such as motivation, attention, and affect (Moran, 2009); (ii) it is frequently reported to improve motor skill acquisition and performance when employed discretely or in conjunction with AE (for a meta-analysis see Feltz & Landers, 1983; Smith et al., 2008); and, (iii) manipulating the speed of a movement during MI biases subsequent AE (Louis, Guillot, Maton, Doyon, & Collet, 2008).

1.1.2 Theories of imagery

Despite its well-established research tradition, the specific mechanisms through which MI exerts its positive effect on AE remain unclear. Some researchers suggest that the mechanism is peripherally-based (Jacobson, 1932; Mackay, 1981; Magill, 2000), while more contemporary researchers suggest it is of central origin (Jeannerod, 1994; Lang, 1979). Researchers supporting a peripherally-based mechanism argue that similar muscle innervation patterns are activated in MI and AE, with the magnitude of the activation much less in MI. In a seminal study, Jacobson (1932) used electromyography (EMG) to demonstrate consistent muscle activation patterns in MI and AE and suggested that the activation in MI was suppressed physical activity. The suppressed physical activity was suggested to prime the motor pathways and facilitate subsequent motor performance. Since this published report some (Guillot et al., 2007; Hale, Raglin, & Koceja, 2003), but not all researchers (Dickstein, Gazit-Grunwald, Plax, Dunsky, & Marcovitz, 2005; Mulder, Zijlstra, Zijlstra, & Hochstenbach, 2004), have demonstrated subliminal muscle activity at the periphery during MI that is consistent with AE. The inconsistent reports have questioned the efficacy of a peripherally based explanation of the mechanism for the performance effects of MI. Many now accept an alternative interpretation that the observed muscle activity represents the incomplete inhibition of muscle output by central processes (Guillot et al., 2007; Jeannerod, 1994; Mulder, de Vries, & Zijlstra, 2005). The extent of this residual EMG 'leakage' (Lang, 1979) is thought to be influenced by the content of the mental image and the inhibition of AE by the cerebellum (Decety, 1996a; Lotze et al. 1999).

An alternative and well-supported theory (Hale, 1982; Hecker & Kaczor, 1988; Smith et al., 2008) relating to the cognitive processes involved in MI is the Bioinformational Theory of Emotional Imagery (Lang, 1979). Similar to Social Cognitive Learning Theory, Bioinformational Theory suggests performance improvement is achieved through an information function. The mental image is said to comprise a set of 'propositions' or units of information that are manipulated to improve motor behaviour. The propositions are accessed through verbal or written scripts that contain information relating to the task (stimulus and meaning propositions) and information relating to the affective responses (response propositions). During MI, the propositions behave as a prototype for action and efferent outflow occurs. The efferent outflow, which is appropriate to the content and quality of the image, may involve eye movements, muscle activation, skin responses, and heart rate (for a synoposis of the experiments supporting the development of the theory see Lang, 1979). In support of the theory, researchers have demonstrated that increases in muscle strength and golf putting performance, similar to that observed through physical practice, can be achieved by using personalised stimulus, response and meaning propositions during MI (Smith et al., 2008). To guide the development of highly personalised MI scripts, Holmes and Collins (2001, 2002) developed the PETTLEP model (see Figure 1.2). PETTLEP is an acronym, with each letter relating to an element of the action that should be considered when delivering an MI intervention. These elements are inter-related and reflect the: physical, environmental, task, timing, learning, emotion, and perspective aspects of the physically performed task.

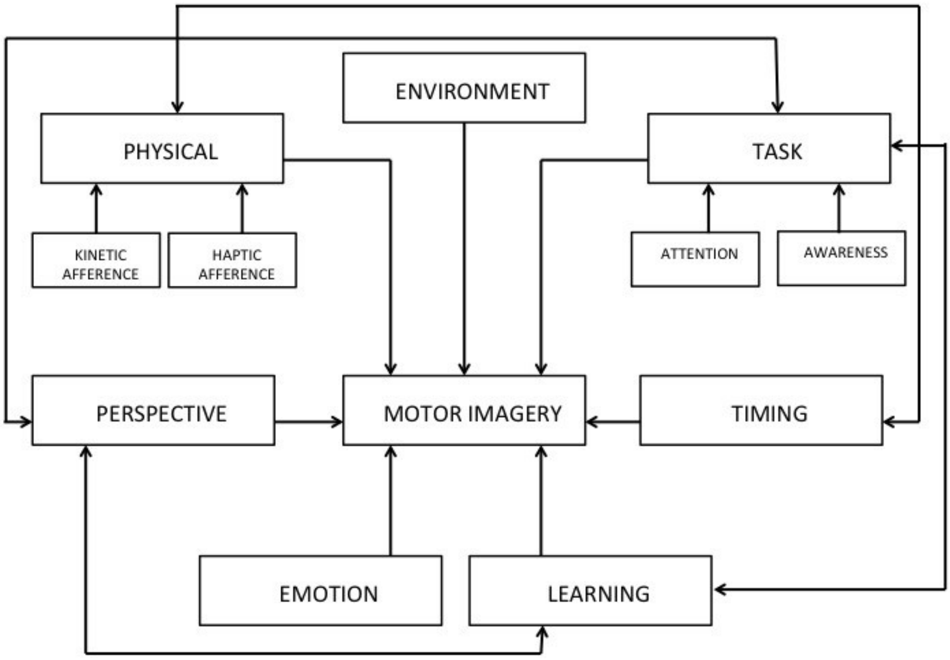


Figure 1-2: Schematic diagram illustrating the interconnectivity of elements of the PETTLEP model of MI. Reproduced with permission (Holmes & Collins, 2002).

In 1994, Jeannerod's Functional Equivalence Hypothesis (Jeannerod, 1994) bridged the gap between traditional cognitive psychology approaches to MI and emerging cognitive neuroscience views. Based on evidence relating to the physiological correlates of MI and AE, the neural structures involved in motor planning and preparation, and the effect of MI on motor performance, Jeannerod suggested that the neural 'sharedness' reflected the hidden part of movement; a representation of the preparation and intention to move. In agreement with Lang (1979), Jeannerod posited that the common representation included information about the event, in particular the goal of the action and the effort and force required to complete the action.

Jeannerod suggested that the representation may evoke physiological responses (changes in heart rate, respiration and eye movements) but, in contrast to the peripherally-based explanation, he argued that performance was improved via central, not peripheral, mechanisms. To support his hypothesis of a central mechanism he drew on studies that had demonstrated interference effects when concurrent AE and MI of dissimilar actions were performed. A similar phenomenon was later identified to exist in AE and AO by Prinz (1997). Over the last twenty years the Functional Equivalence Hypothesis has received much empirical support (see Chapter Two) and Moran (2009) has suggested it is now time to take the next step and uncover the mechanisms underlying the ‘real time’ cognitive processing in these action related processes. This thesis specifically addresses this gap in the literature.

This introductory discussion has outlined the development of AO and MI as individual constructs. Appearing as very different forms of mental practice, the evidence suggests both processes share many parallels with each other and with AE. For example, AO and MI appear to: be based on an information function; generate a representation that is shared with AE; experience interference during the concurrent execution of a dissimilar action-related process; and, be optimised when the tasks are matched to the motor and visual familiarity of the individual. The advent of widely available neuroimaging equipment in the late 1990s has permitted the similarity between AE and AO, and AE and MI to be examined repeatedly at a neural level. Based on this evidence, the Simulation Theory proposed the existence of a partially overlapping neural network in AE, AO, and MI, and suggested that the ‘hidden’ part of the action, the motor representation, is common across all processes.

To date, evidence of a shared motor representation has been demonstrated through central, peripheral, and behavioural markers assumed to reflect equivalence across the three processes. In the following sections the factors that influence the neural sharedness are initially discussed. Subsequently, the markers that are typically used to examine the processes are considered and finally, novel markers that may provide a more comprehensive test and understanding of the Simulation Theory are explored.

2 Literature review

The Simulation Theory (Jeannerod, 2001) suggests that AE, AO, and MI activate common neural areas of the motor system. This idea suggests that the motor pathways associated with one simulation process, referred to as an s-state, may be enhanced via any of the other two through the Hebbian learning principle of 'cells that fire together, wire together' (Holmes & Calmels, 2008; Robertson & Murre, 1999). In support of this assumption, AO and MI have been reported to improve motor performance in music (Bernardi, De Buglio, Trimarchi, Chielli, & Bricolo, 2013), sport (Smith et al., 2008), aviation (Tokumaru, Mizumoto, Takada, & Ashida, 2003), surgical practice (Immenroth et al., 2007), and movement rehabilitation (Ertelt et al., 2007; Holmes, 2007).

The Simulation Theory posits that AO and MI include distinct stages of motor planning that subsequently converge on the same neural structure, possibly the posterior part of the left hemisphere (Farah, Soso, & Dasheiff, 1992; Goldenberg, 1992). Supporting this idea, research suggests that MI involves the computation of a motor plan (Macuga & Frey, 2011), whereas AO maps the dynamic visual information onto a previously acquired motor plan (Rizzolatti et al., 2001). Direct tests of the Simulation Theory have demonstrated that some, but not all, of the neural activation that occurs in AO and MI is also present in AE (Filimon, Nelson, Hagler, & Sereno, 2007; Macuga & Frey, 2011). The extent of the shared neural profile remains the subject of current debate and maybe influenced by many delivery factors such as task content, task instruction, task expertise, modality, and perspective (Holmes & Calmels, 2011; MacIntyre et al., 2013, see Figure 2.1 and 2.2).

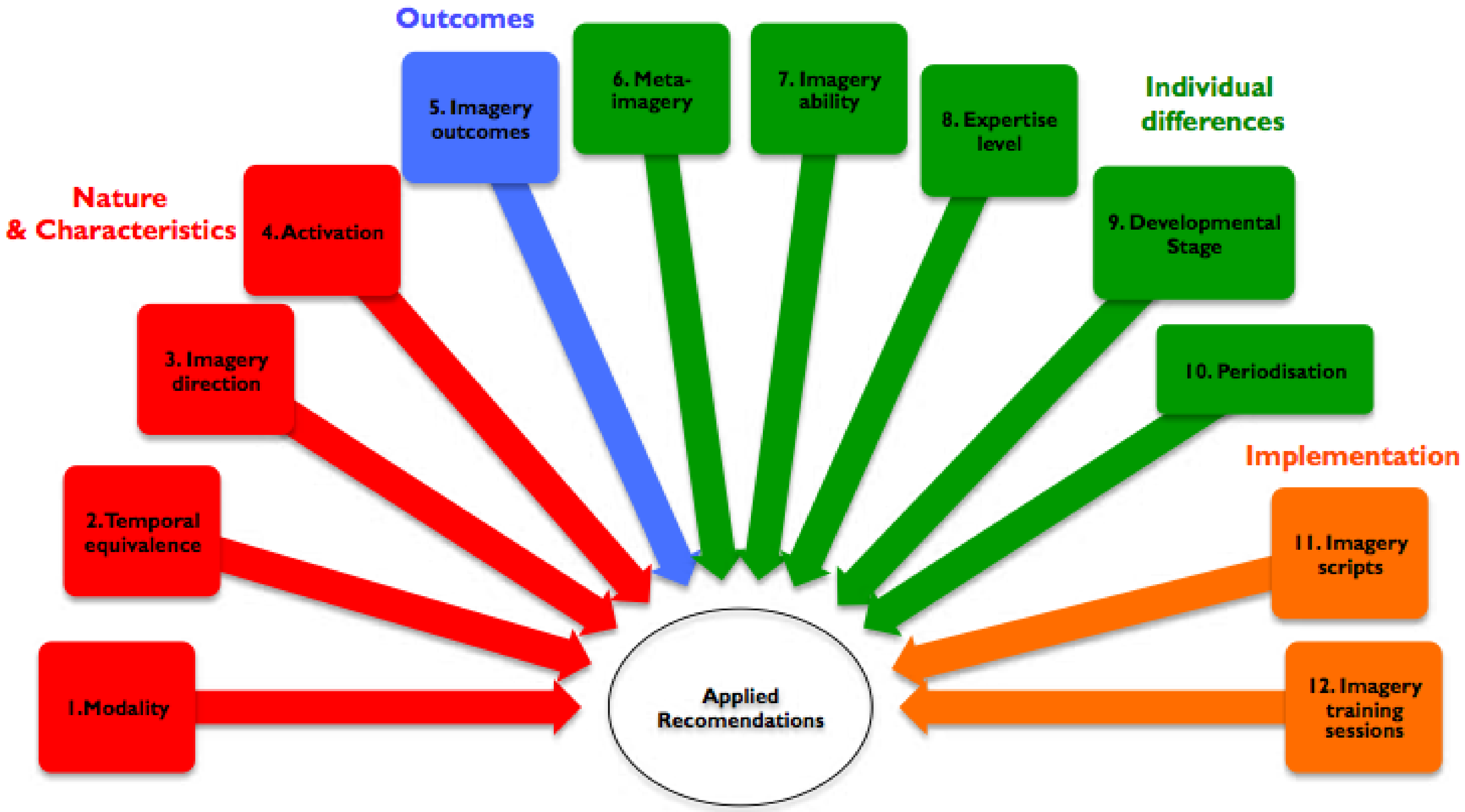


Figure 2-1: Delivery factors for MI (MacIntyre et al., 2013).

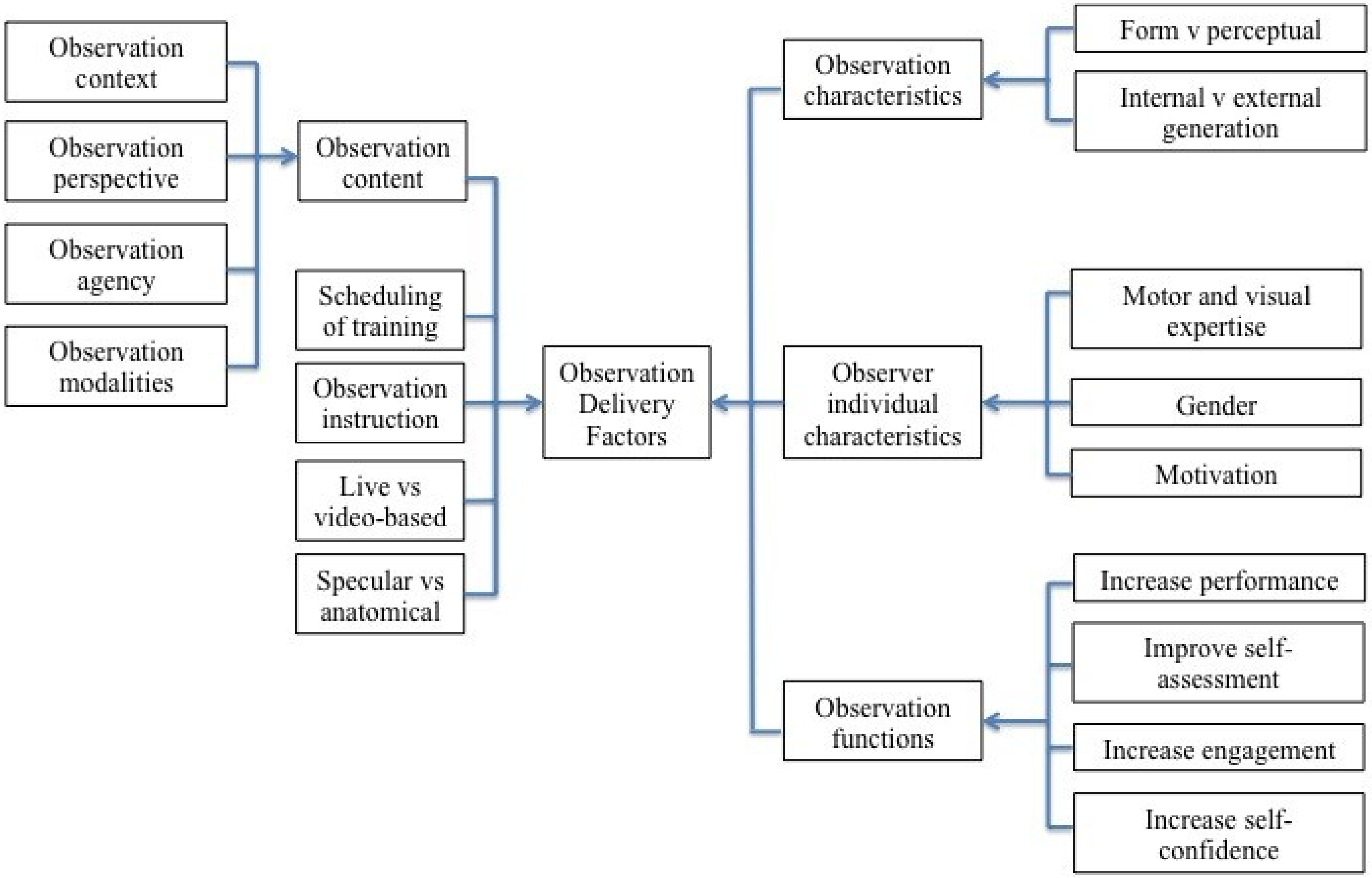


Figure 2-2: Delivery factors for AO. Reproduced with permission (Holmes & Calmels, 2007).

The following two sections discuss some of these simulation factors in the context of sport and clinical rehabilitation. These two domains arguably represent either end of the expert-novice continuum in terms of the cognitive processes, such as attention, memory, knowledge acquisition, and visual search, involved during the performance of skilled movements in dynamic environments. As such, they permit the validity and efficacy of the simulation procedures to be considered.

In the sports domain the effectiveness of AO and MI in motor learning has been linked positively to simulation competence (i.e., MI and AO ability; Lawrence, Callow, & Roberts, 2013) and the motor expertise of the individual (Calvo-Merino et al., 2006; Haslinger et al., 2005). Based on the premise of a shared representation in AE, AO, and MI, this inter-dependency should not be surprising. In skilled individuals the representation becomes highly developed through many hours of physical practice. A shared representation implies that performance gains acquired through one process should influence the other two in a similar way. Thus, enhanced AE should lead to enhanced AO and MI and vice versa. In situations where motor skill is less than optimal, such as with novice performers, AO and MI can be manipulated by perspective to assist the simulation process. A first person visual perspective (1PP) and a third person visual perspective (3PP) are the perspectives most commonly adopted. In a 1PP an action is observed or imagined from an egocentric perspective whereas in a 3PP the action is performed from an allocentric perspective (Holmes & Calmels, 2008). The literature suggests a 3PP is most effective for novice athletes and for skills that depend heavily on form, for example gymnastics (Callow & Hardy, 2004). In contrast, a 1PP is suggested to be most effective when the basic skill is acquired and for skills that depend heavily on perception, for example canoe slalom or penalty kicking (White & Hardy, 1995). Athletes do report switching frequently between perspectives during MI and this may be to supplement the information that is ordinarily available during AE (Hardy, 1997; Smith, Collins, & Hale, 1998).

It is important to note that the literature concerning visual perspective remains unclear and is hindered by researchers using inconsistent methodological approaches and inappropriate task instructions (Moran, 2009). Perspective, agency, and imagery modality are frequently conflated, with researchers often attaching different meanings to common terms (Holmes, 2012). For example, MI from a 1PP is also referred to by some as internal imagery (Callow & Hardy, 2004), and by others (Hale, 1982) as a kinaesthetic modality, or a visual modality (Glisky, Williams, & Kihlstrom, 1996). This confusion may stem, in part, from Jeannerod's early description of MI. In his Functional Equivalence Hypothesis, he described MI as an egocentric process (i.e., a 1PP) that involved a representation of the self in action with the subject feeling himself executing a specific action, often in a visually-represented space. Thus, the MI process included both the visual and kinaesthetic modalities. Conversely, he described the imagination of an action of an agent from an allocentric perspective (3PP) as VI. He suggested that VI could involve the imagination of a person or an object moving but would not involve any kinaesthesis. Since Jeannerod's original definition of MI, some researchers (e.g., Callow & Hardy, 2004; Hardy & Callow, 1999; Stevens, 2005; Ungerleider & Golding, 1991) have demonstrated that kinaesthesis can occur when an action is imagined in the 3PP if the agent of the action is the self and if the imager is specifically instructed to 'feel' the movement. In a series of well-controlled experiments Hardy and Callow (1999) preceded MI (1PP, self, and 3PP, self) with AO videos and personalised MI scripts (weighted with response propositions to encourage physiological responses) and demonstrated that kinaesthesis can be developed in both perspectives. Further, the authors demonstrated that when tasks include a high degree of form-based skills, such as rock climbing, kinaesthetic imagery in the 3PP can be more effective than kinaesthetic imagery in the 1PP. To eliminate confusion in this thesis, and because it has become the accepted term, MI is used to describe the imagination of actions performed in a 1PP *or* a 3PP. In accordance with Hardy and Callow (1999), it is assumed that kinaesthesis can be developed in both perspectives during MI if appropriate instructions are given and if the agent of the action is the self. In contrast, VI typically involves the imagination of a scene which may, or may not, involve an action performed by an agent but does not involve kinaesthesis.

Of particular importance to this thesis is that the concepts of perspective, agency, and modality have been shown to significantly influence neural substrate during the different imagery conditions. Given that the Simulation Theory suggests at least some common substrate across MI and AO, it is intuitive to suggest that these factors will also influence the efficacy of AO. Taken together, the three factors were critical to the methodological designs of the studies repeated in this thesis as they pertain to eye gaze behaviours, and to the development of the AST toolkit discussed in Chapter Six.

In the clinical domain there is increasing evidence supporting the efficacy of action simulation procedures (e.g., AO, MI, mirror box, and virtual learning). Recent findings suggest that mental practice may offer new ways of stimulating motor weakness, regeneration, and plasticity when motor function has been compromised by age, stroke, or neurodegenerative disease. A number of related reviews have proposed the potential of AO and MI in motor rehabilitation (e.g., de Vries & Mulder, 2007; Garrison, Winstein, & Aziz-Zadeh, 2010; Holmes, 2007) as an alternative or adjunct to movement therapies. In addition, a growing number of clinical studies involving elderly patients suffering from Parkinson's disease (Pelosin et al., 2010), dementia (Eggermont, Knol, Hol, Swaab, & Scherder, 2009), and stroke (Butler & Page, 2006) also indicate the benefit of action simulation procedures in movement rehabilitation. Similar to the sports domain, evidence suggests that visual perspective may influence the performance outcome (Ewan, Smith, & Holmes, 2010; Liu, Chan, Lee, & Hui-Chan, 2004). Ewan et al. (2010) demonstrated that individuals affected by stroke improved motor performance when using MI in a 3PP, and preferred using this perspective. The authors reported that the vividness of the MI was impaired in the 1PP and suggested that this may be due to a loss of functional motor activity. These findings would support the view from sport psychology that for less skilled performers a 3PP may be most effective (White & Hardy, 1995). Others (Page, Levine, & Leonard, 2007) have demonstrated that MI from a 1PP is beneficial in stroke rehabilitation. Reconciling these differences, de Vries and Mulder (2007) speculated that a 1PP may potentially lead to recovery of basic motor skills whereas the 3PP may be beneficial for (re)learning the cognitive and planning aspects of movements.

The cognitive and planning aspects of movements are reported to decline with age, irrespective of clinical morbidity (Salthouse, 2009; Salthouse & Lichty, 1985). It is, therefore, surprising how few studies have examined the influence of age on the cognitive processes involved in AE, AO, and MI. The concept of a central sharedness between AE, MI, and AO implies bi-directionality; AO and MI may influence AE and, similarly, AE may influence AO and MI (Schutz-Bosbach & Prinz, 2007). A bi-directional relationship suggests that if efficient AE is compromised through age related changes, then AO and MI may also become sub-optimal. Thus, the use of these mental techniques during the motor rehabilitation of older individuals may reinforce inefficient movement. Researchers who have investigated the influence of age on simulation procedures have typically used comparisons of neural blood flow (Dror & Kosslyn, 1994; Nedelko et al., 2010) or the chronometry paradigm (Skoura, Papaxanthis, Vinter, & Pozzo, 2005; for an explanation of these methods see section 2.1.1 and 2.1.2 respectively). In general, it appears that older adults retain the ability to simulate their own movement but there is some loss of accuracy between the simulated movement and AE. There is also some degradation associated with activating and maintaining the visual component of the representation (Dror & Kosslyn, 1994). These findings suggest that age related changes in AE may also manifest in AO and MI, and this potentially challenges the efficacy of AO and MI as motor (re)learning tools. Understanding how these cognitive processes are influenced by age related changes may permit more efficacious techniques to be developed. This issue is addressed in Chapter Four and Chapter Six of this thesis.

The preceding sections indicated that motor learning may be influenced by the perspective adopted during simulation, and that individuals with reduced motor skill may prefer a 3PP. The 3PP is suggested to offer the individual supplementary information about an action (Hardy, 1997) and to be of benefit during the (re)learning of cognitive and planning aspects of movement (de Vries & Mulder, 2007). It is currently unknown what specific supplementary information is perceived in AO (3PP) and how it represented it in MI (3PP). If, as discussed earlier, MI (3PP, other agent) does not involve kinaesthesis, then only the visual element of motor representation may be activated during MI. This may reduce the cognitive load. However, a movement of the self imagined in a 3PP could require the mental image to be rotated by up to 180°, and this additional cognitive process may increase the demand on working memory. Thus, the influence of perspective (and agency) on the cognitive processes could facilitate or impede motor learning. Given the increasing use of multi-perspective approaches in simulation procedures (Ertelt et al., 2007), it would seem pertinent to understand how visual orientation influences the shared mechanism. These specific issues are addressed in Chapter Five of this thesis.

2.1 Markers of central sharedness

2.1.1 Neural evidence

Some studies have used techniques such as transcranial magnetic stimulation (TMS), electroencephalography (EEG), and magnetoencephalography (MEG) to examine the neural processes in AO and MI. Common and coherent activation of the motor system that is similar to AE has been demonstrated (for a review of the AO literature see Rizzolatti et al., 2001; Roosink & Zijdewind, 2010; Tokumaru et al., 2003) although some activation remains unique to each process. Most studies, however, have used fMRI to examine the shared neural network. This line of enquiry typically involves measuring the level of deoxygenated haemoglobin in the blood (called the blood oxygenated level dependent or BOLD signal) via cerebral scanning. Cube-shaped brain regions called voxels (volumetric pixels) are determined from the scanned images and the pattern of voxel activation is contrasted between the independent conditions. This contrast permits differences in voxel activity to be determined. Although the technique is used widely it is not without spatial and temporal limitations, and it is difficult to determine if increases in regional cerebral blood flow are related to excitation or inhibition processes (Menon & Kim, 1999). Reaching agreement regarding the localisation of the shared areas is often difficult, hindered by different inter-laboratory methodological and analytical approaches (Vul, Harris, Winkielman, & Pashler, 2009). The lack of ecological validity in methods is also a concern for AO and MI research since participants lie in a prone position during data collection, clearly this is not behaviourally equivalent (Wakefield, Smith, Moran, & Holmes, 2013) to the action they are simulating.

The neural activation pattern is highly sensitive and can be differentiated by a number of factors: task type (Nakano, Ueta, Osumi, & Morioka, 2012); task intention (Iacoboni et al., 2005); visual perspective and agency (Ruby & Decety, 2001); visual sensory control (Macuga & Frey, 2011); simulation skill ability (Cui, Jeter, Yang, Montague, & Eagleman, 2007); motor expertise (Calvo-Merino et al., 2006); and, age (Nedelko et al., 2010). In an attempt to eliminate some of these confounding variables, Grèzes and Decety (2001) conducted a meta-analysis which was limited to studies that: measured cerebral blood flow activity in the whole brain; used consistent reporting measures; performed similar cognitive tasks; and, included upper limb movements only. They reported evidence of shared neural activation in putative areas of the hMNS. These areas included: the supplementary motor area (SMA; implicated in motor planning and learning); the dorsal premotor cortex (involved in aspects of motor control that precedes actual movement); the supramarginal gyrus; and, the superior parietal lobule. In the dorsal premotor cortex, activation was greater in AE than MI, and greater in MI that AO. Since the meta-analysis only three published studies (Filimon et al., 2007; Macuga & Frey, 2011; Nakano et al., 2012) have tested the Simulation Theory directly by examining AE, AO, and MI in a single paradigm. Unfortunately, in two of these studies the neural activation may have been confounded by poor experimental control. Filimon et al. instructed participants to view passively rather than view with the intention to imitate. Task instructions such as ‘observe with the intent to imitate later’ have been demonstrated to activate regions involved in the planning and generation of actions, whereas instructions to ‘observe to be able to recognise’ activate memory-encoding structures (Iacoboni et al., 2005). Therefore, the pattern of brain activation during AO may have been confounded by the nature of the executive processing associated with the task instruction. In the Nakano et al. study, no assessment tools were used to confirm MI ability. In a more controlled study, Macuga and Frey (2011) examined the AE, AO, and MI of a bimanual action and presented a visual image of the action in all three conditions. Motor regions involved in the control of bimanual movements (sensorimotor hand areas, SMA and cerebellum) were compared across conditions. Increased activity was observed in bilateral sensorimotor and SMA regions in all three conditions but the level of activity was not consistent across conditions. The cerebellum was only activated in AE and MI and this finding led the authors to suggest that the cerebellum was involved in the computation of a motor command, a process not performed in AO. In their summary, Macuga and Frey proposed a hierarchical model of activation with activation greater in AE compared to MI, and greater in MI compared to AO. These findings have face validity given that a total overlap of neural activation between AE, AO, and MI would lead to both behavioural and agency confusion (Decety & Sommerville, 2003). The interpretation of cerebellar activity during MI conflicts with an earlier interpretation provided by Decety (1996a). Decety suggested that activity in anterior portions of medial cerebellum may reflect the brain's need to *inhibit* the motor commands to avoid overt movement. Motor inhibition would, intuitively, be expected in MI to prevent physical movement typically reinforced through instructions. Decety's interpretation has been supported by others using fMRI (Lotze et al., 1999). These conflicting findings highlight the difficulty in interpreting central brain activity since such activity may reflect congruent functional neural sharedness or in other cases incongruent behaviour in similar neural areas. The difficulty with identifying meaningful brain activity suggests that the Simulation Theory (Jeannerod, 2001) should be examined using cognitive-behavioural markers so that the meaningfulness of the shared neural network may be better understood. The following section provides a discussion of the alternative markers used historically.

2.1.2 Chronometry

Mental chronometry has been used frequently to infer the duration of cognitive operations during MI (Decety, 1996b). Indeed, the robust temporal congruency that appears to exist between executed and simulated actions has, historically, been used as a marker of MI ability; individuals are asked to physically execute and subsequently imagine similar movements and a comparable movement time (MT) is accepted as evidence of MI competence (for a review see Guillot & Collet, 2005a). Thus, like AE, MI appears constrained by a fundamental kinematic law of movement, Fitts' Law (Fitts, 1954). Fitts' Law states that the time needed to move as quickly as possible between two targets is determined by the width of the targets and the distance separating them. In support of shared motor processes, contemporary researchers have used novel paradigms to demonstrate that this fundamental motor principle also constrains AO (Grosjean, Shiffrar, & Knoblich, 2007). The similar influence of task complexity on MT in AE, AO, and MI has led researchers to suggest that the processes employ similar feed-forward models to predict action outcome. In support of this claim, researchers have demonstrated that the neural substrate is sensitive to the kinematic laws of movement in AO (Casile et al., 2010; Eskenazi, Rotshtein, Grosjean, & Knoblich, 2012) and in MI (Lorey et al., 2010). While the total MT of the motor act may be similar in AE, AO, and MI, the timing of the discrete components of the motor act can be very different in MI. In this modality individuals have been observed to speed up or slow down the subcomponents of the task depending on their goal and motor skill (Calmels, Holmes, Lopez, & Naman, 2006). Calmels et al. requested elite gymnasts to execute and imagine a complex gymnastic vault routine. They reported that the temporal organisation of the action was different in MI compared to AE and suggested that individuals choose specific aspects of the task to focus on. These findings suggest that while chronometry provides a robust method of examining simulation at a macroscopic level, additional markers may permit a more microscopic examination of the cognitive process.

2.1.3 Autonomic nervous system

As a working hypothesis, Collet, Di Rienzo, El Hoyek, and Guillot (2013) posited that some markers of the peripheral nervous system, for example heart rate and respiratory frequency, are causally linked to the mental processes involved in motor planning. In their review Collet et al. provided evidence to suggest that if the primary function of the autonomic nervous system is to maintain homeostasis in the individual, then the motor planning phase should comprise physiological commands that are linked to cognitive processes preparing the organism for the intended movement. The measurement of these physiological responses provides an objective and dynamic marker of the mental processes and permits examination of what an individual experiences during simulation. This information can inform the debate on the meaningfulness of the shared neural substrate.

Using respiration frequency and heart rate as dependent variables, researchers have demonstrated positive correlations between AE and AO (Brown, Kemp, & Macefield, 2013; Paccalin & Jeannerod, 2000), AE and MI (Decety, Jeannerod, Germain, & Pastene, 1991) and between AE, AO and MI (Mulder et al., 2005). Mulder et al. used an effortful weight-lifting task and reported an increase in respiration frequency of 35.6% during AO and 31.6% during MI. They also measured heart rate but failed to demonstrate an effect and reasoned that this may be due to the covert nature of this marker compared to the more obvious rise and fall of the rib cage in respiration. These findings highlight the importance of using task relevant visual cues to enhance motor and visual familiarity between the observer and the observed. Their findings for respiratory frequency corroborated the results of an earlier study (Paccalin & Jeannerod, 2000) that demonstrated that respiratory frequency remains relatively comparable between AE and AO. In this particular study the participants observed a model running at an increasing speed in the 3PP. During AO, the participants' respiration frequency was found to increase at a linear rate for most, but not all, of the exercise bout. Demonstrating that respiration is influenced by the intensity of the observed effort provides key evidence that the autonomic nervous system is active during AO in a similar manner to AE, and that visual cues are important (Collet et al., 2013).

The relative similarity in the physiological responses outlined above suggests that what an individual perceives or imagines during movement simulation is linked to similar processes in AE. The measurement of physiological responses permits a more detailed and dynamic examination of the neural sharedness that is absent in chronometric comparisons. It may, however, still mask some of the processes involved. For example, some changes in the physiological response may be 'lost' by the interdependence of the sympathetic and parasympathetic branches of the autonomic nervous system; the sympathetic branch may increase heart rate in anticipation of an upcoming action whilst the parasympathetic branch may serve to decrease heart rate to maintain homeostasis. In support of this suggestion some (Brown et al., 2013; Decety et al., 1991), but not all (Mulder et al., 2005; Paccalin & Jeannerod, 2000), researchers have observed heart rate to co-vary with the rate of simulated running intensity. Decety et al. (1991) asked models to stand on a treadmill while they performed their MI. In contrast, participants sat in a chair in Mulder et al. and Paccalin and Jeannerod's studies. Standing in a running position may have elicited a stronger motor representation response, being more behaviourally equivalent behaviour to AE (Holmes & Collins, 2002) due to the functional kinetic afference and proprioception.

The above findings support a PETTLEP approach to movement simulation (Holmes & Collins, 2001); behavioural functional equivalence in MI and AO is optimised by the inclusion of relevant sensory input. Indeed, Paccalin and Jeannerod

(2000) reasoned that the detail of the visual stimuli used in their study may have inadvertently disrupted the linear respiratory response. They suggested that relatively small changes in the frequency of the gait cycle during running at a moderately fast speed were too subtle to influence the motor representation and, by extension, the respiratory response of the observer. The work of Calvo-Merino et al. (2006) would suggest that more experienced runners may have been influenced to a greater extent by these subtle changes. Brown et al. (2013) reported that the AO of a model running from a 1PP influenced respiration frequency but this was to a much lesser degree than that reported by Paccalin and Jeannerod, who used a 3PP. These differences may be reconciled if one considers that the visual information related to form is richer in the 3PP compared to the 1PP. As such, the additional information may supplement the information ordinarily available to the performer (observer) in the 1PP. It may also be possible that the observer is able to acquire functionally-meaningful visual information from the model's behaviour (for example, respiratory rate and depth; see Mulder et al., 2005). These task relevant cues, akin to Langian stimulus and response propositions, would seem to be important to the content and development of meaningful AO 'scripts'. This suggests that attentional processes involved in the acquisition and processing of relevant visual information maybe key factors influencing the congruency between AE, AO, and MI. It would seem sensible to consider these cognitive processes in a comprehensive test of the Simulation Theory.

2.2 Eye movements

Vision is frequently considered to be the dominant sensory system underpinning human function (Causer, Janelle, Vickers, & Williams, 2012), and the processes and mechanisms by which vision aids and controls movement have been researched extensively (Elliott, Hayes, & Bennett, 2012). During perception, external visual information is suggested to be retinoptically mapped (preserved) onto topographically organised areas in the occipital lobe. The ‘attended’ environmental visual cues are then processed via the dorsal, ventral, and rostral streams of the visual system; the dorsal stream permits identification of object location, size and orientation, the ventral stream facilitates object recognition, and the rostral stream acting as a conduit between both (Goodale & Milner, 1992). In the dorsal stream, which extends from visual cortex into posterior parietal cortex, the visual and other sensory information is transformed into a common eye-centred frame of reference in motor areas to guide movement (Andersen, Snyder, Bradley, & Xing, 1997; Desmurget et al., 1999).

As the gaze control system comprises mechanisms concerned with the acquisition of visually presented information, it is considered an excellent reflector of cognitive processes such as decision-making and attention (Vickers, 2009). Although the extent to which gaze behaviour represents the amount of cognitive processing has been questioned (Posner & Raichle, 1994; Viviani, 1990), recent research suggests that it is difficult to shift the point of gaze without shifting attention (Shinoda, Hayhoe, & Shrivastava, 2001). The attention shifts that precede saccadic eye movements are associated with their preparation and involve some of the same neuronal ‘machinery’ (Corbetta et al., 1998; Culham et al., 1998). Corbetta et al. examined fMRI and surface-based representations of brain activity to compare the functional anatomy of two tasks, one involving covert shifts of attention to peripheral visual stimuli, the other involving both attentional and saccadic shifts to the same stimuli. Overlapping regional networks in parietal, frontal, and temporal lobes were active in both tasks. This anatomical overlap is consistent with the hypothesis that attentional and oculomotor processes are tightly integrated at the neural level. Motter and Belky (1998) and Findlay and Gilchrist (1998) have also argued that fixations reflect attentional distribution in visual search experiments. Accordingly, researchers rely extensively on markers of gaze behaviour to infer the attentional processes involved in the execution of visuomotor tasks (Abrams, Meyer, & Kornblum, 1990; Hayhoe, 2004; Land, Mennie, & Rusted, 1999; Vickers). In reach and grasp tasks, visual fixations (brief periods of time when the eyes are stable and focusing on visual cues) typically precede motor manipulation (Abrams et al.). The location and duration of these unique eye movements are considered to perform two vital monitoring functions. First, they identify the goal directed target and second, they provide visual feedback about the grasping hand to enable online corrections (Brouwer, Franz, & Gegenfurtner, 2009; Land et al.). Cognitive psychologists interpret the spatial and temporal distribution, and duration of the fixations as reflecting the cognitive processes used in movement execution (Vickers). Seminal work by Woodworth (1899) suggested that once a stationary target is fixated, a single ballistic movement occurs that brings the limb into the vicinity of the target and this is then followed by a single corrective movement that is based on visual feedback about the relative positions of the limb and target. More contemporary work (Desmurget & Grafton, 2000; Khan et al., 2006) has, however, suggested that the ballistic phase of the movement is not as predetermined as first thought. Desmurget and Grafton reported that the limb may be under continuous control, with movement determined through the comparison of the early dynamic information from the limb with an internal model associated with the movement planning process. This suggests that the continuous motor control comprises graded fluctuation in muscle forces driven by the dynamic, online, functions of visual and proprioceptive feedback from the limb.

In the sports domain, economical gaze strategies during aiming tasks are reported to involve fewer fixations of longer duration to the critical visual cues (Shapiro & Raymond, 1989; Vickers, 1996; Williams, Singer, & Frehlich, 2002). The duration of the final fixation prior to movement onset has been identified as a particularly important marker. Referred to as the 'quiet eye' (QE; Vickers), the location, onset, offset and duration of this specific fixation are considered to represent aspects associated with the preprogramming of the movement (Vickers, 2009). In certain tasks, such as the golf swing, the QE duration is also considered to reflect online control (Vine, Lee, Moore, & Wilson, 2013). There is increasing evidence to suggest that when the parameters of this unique fixation are trained (i.e., when individuals are taught how to optimally control their gaze), the performance gains are much greater than when physical or psychological training regimes are used independently (Vickers). The QE has been examined in sport, law enforcement, medicine, and the military. It has, however, received little consideration during mental simulation procedures. If the QE reflects the cognitive processes associated with motor planning and online control, then, in accordance with Simulation Theory, it may be intuitive to expect aspects of the phenomenon to occur in AO and MI. If there is evidence to support this claim, potential may exist to optimise (re)learning through these covert techniques by exploiting the plasticity of the parameter. This idea is explored further in Chapter Six of this thesis.

2.2.1 Eye movements in action observation and action execution

Seminal work by Flanagan and Johansson (2003) demonstrated that eye movements in AO were related to the shared motor representation. Using a block-stacking task, Flanagan and Johansson compared the location and temporal execution of fixations during AO (3PP, other agency) and AE. They reported that eye movements in AO were spatially similar to, and in phase with, the fixations performed in AE. In both simulation conditions participants attended proactively to the upcoming point of contact (block pick up or set down) and were considered to be anticipating the outcome of the action rather than attending to its visual unfolding. The authors suggested the execution of similar, proactive fixations in AO and AE provides evidence that the neural processes are linked and that the motor representation includes directions for the visual system. These data are supported by Brouwer et al. (2009) who demonstrated a different eye movement pattern depending upon whether the action involved the viewing of a stationary object or the reach and grasp of that object. During viewing, the eyes fixated the centre of mass of the object, whilst during reach and grasp the eyes predictively fixated the future contact areas of the index finger and thumb.

In a more recent study, Ambrosini, Costantini, and Sinigaglia (2011) examined whether the shared representation transferred into more complex scenarios. In this study a variety of objects of varying shapes and sizes were used that demanded the actor to execute one of two different handgrips. A control condition was also included in which the actor did not pre-shape their hand. The results showed that in the pre-shaping condition the observers demonstrated earlier saccadic eye movements and higher hand position accuracy compared to the control condition. These data suggest that simply pre-shaping the hand is enough for an observer to identify a target object, and engage the same motor representations as that employed during AE. Building on these ideas, Ambrosini, Sinigaglia, and Costantini (2012) asked participants to observe an actor reaching for a target object whilst their hand was either free to move or restrained. Gaze behaviour was compromised significantly in the restrained condition, leading the authors to conclude that it is critical for the observer to be under the same constraints in AO and is in AE. These findings would support Holmes and Collins' (2002) PETTLEP model of MI, that the congruency of the gaze metrics appears enhanced when the other sensory inputs are matched. Collectively, these studies suggest that similar attentional processes are used in AE and AO. When the tasks are predictive, eye movements in AO appear to proactively seek out the target and are spatially similar to those in AE.

In conditions where the task goal is unknown or ambiguous, the observer makes use of subjectively salient cues to help determine the action goal. When AO is from the 3PP, observers are reported to fixate the agent's head initially and this may be due to an innate desire to establish joint social attention or to acquire early cues relating to the task goal. (Letesson & Edwards, 2012; Webb, Knott, & Macaskill, 2010). This behaviour highlights an important issue in AO; active vision is guided not only by the action but also by the vagaries of the visual scene. Thus, an individual may be presented with the correct action cues but they may not attend to the critical cues at the critical time (Loftus & Mackworth, 1978). These factors may be of particular importance in elderly populations where the efficiency with which observers extract visual information is decreased (Sekuler, Bennett, & Mamelak, 2000), and in clinical populations where the perceptual sensitivity to the actions of others has been influence through functional motor inactivity. If the spatial and temporal aspects of visual cues are attended to incorrectly during AO, the effectiveness of this process as a motor (re)learning technique may be compromised. This idea is explored further in Chapter Five.

2.2.2 Eye movements in motor imagery and action execution

The presence of task-related eye movements in VI has been argued for over eighty years (Brandt & Stark, 1997; Hebb, 1968; Jacobson, 1932; Laeng & Teodorescu, 2002). As early as 1968 Hebb (Hebb, 1968) hypothesised that "if the image is a reinstatement of the perceptual process it should include the eye movements" (Hebb, 1968, p. 470). Although this postulate refers to VI, the claim may also apply to MI given that MI involves actions taking place within represented visual space (Jeannerod, 1994). Rodionov, Zislin, and Elidan (2004) were one of the first groups to examine eye gaze in MI (1PP). Specifically, they questioned whether imagination of body rotation could induce occulomotor activity similar to the typical vestibulo-ocular reflex. Their data suggested that nystagmic activity in the horizontal plane could be elicited during MI and provided early evidence that eye movements could be used as an objective measure of online cognitive processes. More recent research has confirmed the significant role of other gaze metrics during MI. For example, Heremans, Helsen, and Feys (2008) compared eye movements during the AE and MI (1PP) of a cyclical aiming task. Addressing the phenomenon that many individuals close their eyes spontaneously during MI they included two MI conditions, one with eyes open and one with eyes closed. Their results showed that over 80% of participants made task-related fixations during MI with the eyes open and eyes closed. Furthermore, both the number of fixations and inter-fixation amplitude MI closely resembled the fixations made during AE. In a follow up study (Heremans et al., 2009) the authors also demonstrated that the congruency of gaze metrics in AE and MI (1PP) was enhanced when the MI was assisted with visual and auditory cues (similar to those used during AE). These findings resonate with the VI literature. VI is reported to comprise two distinct types, one that involves allocating attention to specific regions of space (attention-based imagery) and one that involves activating stored visual memories (visual-memory based imagery; Kosslyn, 1993). Attention-based imagery is suggested to be facilitated when a visual structure is provided by the environment rather than it having to be generated internally. Thus, in the Heremans et al. study, the congruency between the gaze metrics may have been enhanced because the participants performed 'attention-based' MI. Supporting MI by providing a visual structure could be of benefit in elderly populations where the ability to activate a stored visual representation and maintain an image is reported to degrade (Dror & Kosslyn, 1994).

In attempts to explain the role of eye movements during MI, researchers have employed chronometry paradigms and included conditions in which the eyes are fixed or free (Gueugneau, Crognier, & Papaxanthis, 2008). Gueugneau et al. demonstrated that the temporal similarity between AE and MI (1PP) was maintained when eyes were fixed or free, but that both tasks were speeded up, and temporal congruency between AE and MI enhanced, in the eyes free condition. These findings suggest that in both conditions a shared motor representation was generated but the quality of the representation was compromised in the eyes-fixed condition where information was acquired through peripheral vision only. This study highlights that performance in AE and MI may be compromised if eye movements are less than optimal and supports the Hebbian argument that similar eye movements are executed in MI and AE. In addition, the study demonstrates how a combination of markers (chronometry and eye movements) can help inform the meaningfulness of the shared neural substrate.

The studies reviewed in this section imply that spatially-similar eye movements are performed in AE and MI (1PP). This general consensus belies the debate that surrounds the purported mechanism for the phenomenon. Kosslyn (1987) suggested the eye movements in VI are used to access a ‘visual buffer’, a storage medium in visual parts of cortex that is activated during VI. During perception, visual information is stored in the visual buffer alongside spatio-topic information relating to where the objects are in space. This spatio-topic information has been suggested to be indexed using eye movements. During VI, the mental image is activated in the visual buffer with the spatial aspects of the image retained through the re-enactment of the eye movements that were executed during perception. There has been some support for Kosslyn’s Visual Buffer Hypothesis (Brandt & Stark, 1997; Laeng & Teodorescu, 2002) but not all researchers accept the theoretical account (Johansson, Holsanova, & Holmqvist, 2010; Thomas, 1999). Johansson et al. demonstrated that when a central fixation is maintained during scene perception, spontaneous eye movements still occur during scene generation in VI, and that the eye movements reflect the task but with some loss of accuracy. These findings suggest that the eye movements in VI are not a re-enactment of those performed in perception but represent some other phenomenon. Johanasson et al. posited that eye movements may be performed in VI to relieve the working memory load; eye movements do not have to be executed but are likely to be executed when the task is complex. The interpretation has parallels with the functional role of eye movements in AE. Simple tasks can be performed in the absence of eye movements but increases in task complexity typically influence the number of fixations and/or the fixation duration (Williams et al., 2002). A similar explanation also been used to interpret the findings of some eye gaze studies in MI (Debarnot et al., 2011). The idea of a visual buffer has also been disputed by others (Thomas, 1999). Thomas suggested that eye movements in VI do not re-enact the perceptual phase but rather they inspect the imagined scene as if it were actually present. In this hypothesis, the eye movements in VI are likely to be similar to perception but they are executed independently and not coupled to a visual index. Notwithstanding the contrasting views for why eye movements occur during simulation, the general view from this section is that eye movements perform a functional role that is linked to action understanding. A clearer understanding of the extent of the shared mechanism in relation to eye movements may permit motor (re)learning techniques involving MI to be optimised. This topic is revisited in Chapter Six.

2.2.3 Eye movements in action observation and motor imagery

Few researchers have compared eye movements during AO and MI. Given that the motor representation is suggested to be shared between AE, AO, and MI, it is intuitively appealing to suggest that similar eye movements should be executed in AO and MI. McCormick, Causer, and Holmes (2012) compared a number of fixation parameters during the AO and MI (1PP and 3PP) of a reach-grasp-place action. In this study, participants observed a model reach for a cup and place it on a saucer, presented in the 1PP and 3PP. Subsequently, the participants performed MI in the same perspective as the AO. The authors recorded fewer fixations at the critical movement cues in 3PP compared to the 1PP, and reported that fixation duration was duration was significantly longer in AO. In accordance with Shapiro and Raymond (1989), the findings for fixation duration suggest that a more economical gaze strategy was executed in AO. The less economic gaze pattern in MI may be due to the lack of visual cues or the absence of prior practice. Indeed, others have reported that MI is facilitated when it is primed by AE (Mulder et al., 2005). Mulder et al. reported that respiration frequency during MI (1PP, self-agency) was significantly increased when the MI was performed after AE compared to when it was performed before. These findings support the idea of a shared motor representation and suggest that the combination of simulation procedures and perspective should be considered when these processes are used in motor (re)learning.

McCormick et al. (2012) speculated that the reduced number of fixations to the regions of interest (ROIs; Cup Pick Up and Cup Placement) in the 3PP may have been due to an innate desire to establish joint social attention. Evidence from sport psychology suggests a 3PP may be beneficial because this perspective provides additional anatomical cues. Eye gaze studies, however, appear to suggest that a 3PP shifts the focus from anatomical cues to social cues (Castiello, 2003). If gaze strategy is as critical to motor learning in AO and MI as it is in AE, then it would seem pertinent to understand the influence of social gaze during simulation procedures. This issue is examined in detail in Chapter Five.

2.3 Overview of studies

The primary aim of this thesis was to test Jeannerod's Simulation Theory (Jeannerod, 2001) using gaze metrics. A second aim was to identify the processes by which individuals acquire information in AE, AO, and MI and to use this knowledge to design an evidence based motor simulation tool for movement (re)learning. A novel experimental paradigm was devised to compare the eye movements of healthy individuals in AE, AO, and MI, and to examine the influence of early ageing on the gaze metrics. Subsequently, a novel approach to examining the influence of perspective was developed. Finally, an empirically-driven action simulation-based therapy intervention to support the physical treatment of upper limb function was designed and prototyped. Specific hypotheses are presented in each of the individual chapters.

Currently, there are few empirical studies that have tested the Simulation Theory directly and none have used gaze metrics. Chapter Three reports how visual search differs between AE, AO, and MI and uses fixation metrics to indirectly compare the posited neural overlap. The intention was to identify common and specific gaze metrics in AE, AO, and MI, providing insight into the meaningfulness of the shared neural substrate and the cognitive processes employed. Using a similar protocol to the study described in Chapter Three, Chapter Four examines the influence of ageing on the congruency of the gaze metrics.

After identifying typical gaze characteristics in AE, AO, and MI, Chapter Five aimed to use eye movements to examine the influence of perspective on simulation procedures. The specific objectives of this study were: (i) to understand if and how the 3PP is represented during MI; and (ii), to examine the influence of prime perspective during simulation.

The aim of the final study in Chapter Six was to develop an Action Simulation Training (AST) toolkit to support the physical treatment of upper limb function. The findings of the eye gaze studies in this thesis were considered in the context of a prototype rehabilitation aid. The AST toolkit was conceived as an empirically-based, best practice model to facilitate motor (re)learning and future research.

To conclude, Chapter Seven provides a synthesis the findings from this programme of work and provides a clear and concise summary of both the theoretical and applied implications of the thesis. Future research directions are discussed and limitations of the programme of work identified.

3 Study 1: Active vision during action execution, action observation and motor imagery

3.1 Introduction

Chapters One and Two discussed the use of MI and AO to improve motor performance and the proposal that both MI and AO access the same neural substrate as AE. In support for these claims, evidence was provided that the interdependence between these action-relation cognitive skills may be linked closely to their neural anatomical-equivalence (e.g., Filimon et al., 2007; Macuga & Frey, 2011), and that all three processes are constrained by a fundamental law of human movement, Fitts' Law (Decety, Jeannerod, & Prablanc, 1989; Grosjean et al., 2007). This evidence of neural 'sharedness' was identified as an important marker within Jeannerod's Simulation Theory (Jeannerod, 2001).

The Simulation Theory is frequently used as a mechanism to explain the improvements in motor performance following AO and MI. The burgeoning support for this theory belies the number of studies that have directly tested its main tenets, i.e., examined the neural sharedness by including all three process in a single paradigm. The few studies that have adopted this approach (Filimon et al., 2007; Macuga & Frey, 2011) have primarily focussed on comparisons of neural blood flow. Although this marker can be used to indicate cortical activity, it is not without limitation (see section 2.1.1). A more detailed interpretation of the neuronal activity is required if the mechanism is to be fully explained. It would therefore seem pertinent to include all action related process in a single experiment and to consider markers that permit the cognitive process to be examined in 'real time'.

An emerging method of comparing cognitive processes is eye gaze registration (Moran, 2009). As discussed in the introductory chapter, contemporary researchers have demonstrated that fixations are congruent between AE and MI (Heremans et al., 2009), AE and AO (Flanagan & Johansson, 2003), and AO and MI (McCormick et al., 2012). Although these studies suggest that similar cognitive processes (e.g., attention) are performed in AE, AO and MI, the inclusion of only two of the three processes in any one study does not constitute a direct test of the theory. A comprehensive inter-process comparison using eye movements would address this shortfall.

In the current study, the Simulation Theory was comprehensively tested using eye movements. Fixation metrics were compared across AE, AO and MI conditions. All participants performed a reach and point task at three levels of complexity, defined by target width. MT was measured in AE and MI to confirm task compliance. Based on the tenets of Jeannerod's Simulation Theory it was hypothesised that: (i) MT would be congruent between AE and MI; (ii) the number of fixations to the target location would remain congruent in all conditions; and (iii) total target fixation duration would be congruent across all conditions.

3.2 Methods

Following purposeful sampling, a homogeneous group of thirteen healthy participants volunteered to participate in the study. All participants had normal or corrected to normal vision and were right handed as assessed by the Edinburgh Handedness Inventory (EHI; 96.12 ± 4.36; Oldfield, 1971; see Appendix A). The age range of participants was 51.49 ± 6.01 years. The motor and cognitive skills of the participants were assumed to be unimpaired as age related slowing in AE, AO, and MI is suggested to increase from 60 years (Dror & Kosslyn, 1994; Leonard & Tremblay, 2007). All participants were naïve to the hypotheses being tested and provided written consent to take part. The protocol were approved by a Departmental Ethics Committee at the Manchester Metropolitan University and conducted in accordance with the Declaration of Helsinki.

Measures

The Movement Imagery Questionnaire – Revised Second Version (MIQ-RS, Gregg et al., 2010; see Appendix B) was administered to measure MI ability. This questionnaire comprises 14 items; seven VI items and seven kinaesthetic imagery items. The completion of this questionnaire requires participants to imagine movement tasks such as a knee or arm raise and then rate the ease with which they were able to perform the imagery. Ratings for each item on the MIQ-RS are selected from a 7-point Likert-type scale where 1 = very hard to see/feel and 7 = very easy to see/feel. Possible scores therefore range from 14 (extremely poor imagery ability) to 98 (extremely good imagery ability) for the combined modalities. Following the recommendation of others (Fourkas, Ionta, & Aglioti, 2006; Goginsky & Collins, 1996), an in-house questionnaire (see Appendix D) was also administered post-experiment to subjectively assess participants' MI and AO performance. The questionnaire used a 7-point Likert-type scale (similar to the MIQ-RS) to rate the ease/difficulty associated with the participant's visual and kinaesthetic performance in MI and their active visual engagement and kinaesthesis in AO.

When this study was undertaken there was no psychometric tool available to measure the ability to observe an action. The Functions of Observational Learning Questionnaire (Cumming, Clark, Ste-Marie, McCullagh, & Hall, 2005) is a tool used to determine an individual's motivation for using AO but it does not measure AO competence. Recently, Lawrence et al. (2013) reported that MI ability (assessed via the VMIQ-2) moderates the relationship between AO and imitation learning (AE). Thus, given that the participants recruited in this programme of work had at least average MI ability (albeit assessed through a different validated questionnaire) it is likely that they also possessed above average AO skills.

Eye movements were recorded using an Applied Science Laboratories (ASL) Mobile Eye system (Bedford, Massachusetts). The system uses a method known as 'Dark Pupil Tracking' in which the relationship between the pupil and three harmless near infra-red lights projected onto the cornea is computed to locate gaze within a scene. The equipment samples at a rate of 30 Hz, has a system accuracy of 0.5° of visual angle, a resolution of 0.10° of visual angle, and a visual range of 50° horizontal and 40° vertical. A fixation was defined as a stable gaze position (i.e., within 0.67 ° visual angle) that was maintained for at least 120 ms. Pilot testing of the task revealed no significant horizontal eye movements and therefore only vertical gaze was analysed. Individual 'look-zones' were overlaid onto each target during post processing and all fixations within these zones were analysed. The look-zones were equivalent to the target size plus a tolerance: large target = 6 mm^2; medium target = 7 mm^2; small target = 8 mm^2. The tolerance accommodated for drift, compressions, expansions and individual gaze behaviour preference (Laeng & Teodorescu, 2002). A similar method of spatially comparing fixations between simulation states has been employed by others (Laeng & Teodorescu, 2002; Richardson & Spivey, 2000). The equipment was operated from outside the testing booth to eliminate experimenter distraction. A chin rest was used to restrict head movements and participants were requested to refrain from talking whenever possible. The equipment was calibrated immediately prior to the experiment using a 9 point grid which was presented on the tablet once the participants were seated appropriated.

Goal directed task

A goal-directed reach and point task was used to examine the internal model associated with the motor planning processes involved in AE, AO, and MI (see Figure 3.1). The neurological profile associated with simple reach and point tasks is reported to be influenced depending upon whether the task is discrete or rhythmic i.e., simple harmonic sinusoidal oscillation between two targets (Schaal, Sternad, Osu, & Kawato, 2004). As rhythmical tasks become more complex, the kinematic profile of the limb is reported to shift from continuous motion to a concatenation of discrete movements, where the forward and reverse arm movements are punctuated by a short dwell time at the target (Mottet & Bootsma, 1999). To control for this potential confound in movement kinematics, participants performed a series of 11 discrete forward reach and point movements. The task, referred to as a Virtual Fitts' Task (VFT), represented a modified version of the Virtual Radial Fitts' Task previously employed by others (Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009; Heremans et al., 2011). It is important to note that the MI condition comprised the 1PP only. This approach was adopted for a number of reasons. First, it is consistent with the interpretation of MI within a strict

Jeannerodian understanding of motor imagery. Second, MI has been interpreted in this way by other researchers (e.g., Heremans et al., 2008), and third, perspective sub elements (1PP and 3PP) have different neural substrate signatures. Therefore, whilst kinesthesis can be experienced during 3PP, as discussed in Chapter Two, the study in this chapter was delimited to a single perspective of 1PP.

The tasks were performed using a calibrated (pre-experiment) tablet (ST2220T, Dell United Kingdom Inc.) and a hand held stylus (normal pen size and weight). The tablet had a spatial accuracy ± 2.5 mm over 95 % of touchable area and a typical response time of 15 ms. The experiments were hosted in DMDX (Forster & Forster, 2003). This windows based programme precisely controlled the timing and presentation of participant instructions and the action related stimuli. The stylus movements were recorded at 50 Hz using this software. Participants held the stylus in their right hand and performed the VFT in: (i) AE; (ii) MI; and (iii) AO. In the majority of conditions (see note below) a HOME and FINISH button together with a TARGET square were presented on the tablet (see Figure 3.1). The HOME and FINISH buttons were positioned approximately 200 mm away from the participant's torso (midline). The TARGET was vertically aligned with the HOME button and the amplitude between the closest edges of the HOME and TARGET was constant (185 mm). Three TARGET squares of different sizes were used: large (20 mm^2), medium (9 mm^2), and small (4 mm^2). The size of the TARGETs led to three indices of difficulty (ID), 4.2, 5.4 and 6.5 respectively ($ID = \log2 (2A/W)$; Fitts, 1954). Note: The MI condition consisted of two sub conditions, guided MI (GMI) and unguided MI (UMGI). In GMI the HOME, FINISH, and TARGET buttons were presented. In UGMI the HOME and FINISH buttons were presented but the TARGET button was not presented. Thus, in the UGMI conditions the participants had to imagine the location of the TARGET as well as the movement to and from the TARGET. The GMI and UGMI were included as distinct conditions as MI may not always be performed with the assistance of relevant visual cues.

In AE and MI (GMI and UGMI), the HOME button was tapped to begin the task. In AE, participants physically moved the stylus to the TARGET, back to HOME and then to FINISH. In MI, the same action was imagined but without any concomitant movement to the TARGET. The MT, the time from when the stylus left the HOME button until it pressed the FINISH button, was recorded in both AE and MI. In AO, the participants held the stylus and observed a recording of the movement. Note: To promote intra-individual congruency between conditions, participants' AE trials were covertly filmed using a Sony High Definition Handycam (HDR-HC7E). The camera was positioned directly above the participant, 186 cm from the floor. The participants were unaware that their AE trials were being filmed, however, the experimental protocol was later explained during the final debrief session. The personalised videos were then presented onto the tablet during the participants' AO trials.

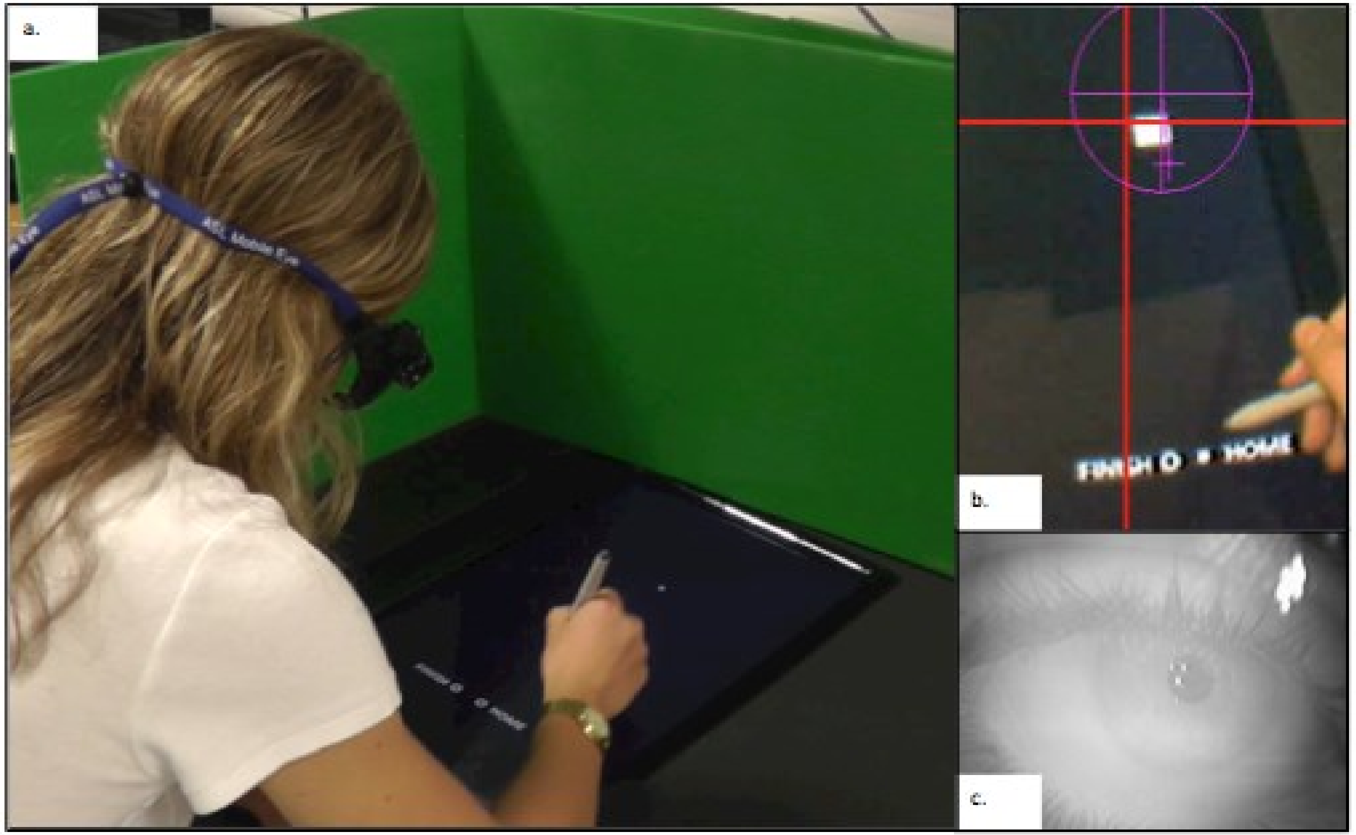


Figure 3-1: a)Participant performing the VFT in AE; b)view from the Mobile Eye scene camera with red cross-hairs indicating point of gaze; and c) the eye with the three harmless near infra-red lights that are used to measure movement.

Control

To ensure that the eye movements in the simulation conditions did not reflect random oculomotor behaviour a control condition was included. In this condition the TARGET, HOME and FINISH buttons were presented on the tablet and participants were instructed to count back slowly from 100. After 60 s (a time equivalent to the mean time spent performing a complete block of repeated tasks in AE) the participants were asked to rest. To ensure a maximally homogeneous task across all participants a series of instructions were issued. In AE, participants were requested 'to move the stylus as quickly as possible but not to risk improving speed at the expense of accuracy'. In MI, participants were instructed to use MI from a first person egocentric, visual orientation. To control the MI, a brief script was recited by the experimenter which described the scenario and the imager's inner response to the scenario (Lang, 1979): 'see yourself accurately reach the square target, as if you were actually performing the movement' and 'feel your grip on the stylus, feel the muscles in your upper arm contract, feel your arm extend as you perform the movement'. Participants were requested to refrain from any upper limb movement in this condition. In AO, the participants were instructed to remain stationary and to 'observe the action with the intention to imitate it at a later time'.

Experimental procedure

Participants were fitted with the eye tracking system and initially performed a single habituation block of the VFT using a target that was a different size (15 mm^2) to the experimental tasks. Participants were then assigned to one of three starting series defined by target size (large, medium, small). Each series began with one block (11 repeated reach tasks) of AE, followed by one block of each of the other conditions, i.e. MI, AO, and Control, counterbalanced (see Figure 3.2). Preceding AO and MI conditions with AE was a necessity to maintain equivalent self-referent representations based on stored memories of the prescribed task (Borst & Kosslyn, 2008). Each block consisted of 11 repetitions of the task followed by a 120 s rest. Following each rest period the calibration of the Mobile Eye was checked. At the end of the experiment each participant was debriefed fully and manipulation checks were performed to confirm participant compliance in the covert tasks.

Chronometry

Performance on the VFT was measured by comparing each participant's mean MT. The AO condition was excluded from this analysis as no MT data were recorded. If effective MI was performed, MT would be comparable between MI and AE, and both GMI and UGMI conditions would be influenced by task complexity.

Total number of fixations

The total number of fixations inside the look-zones (per block of trials) was calculated and compared between conditions. Based on the work of Flanagan and Johansson (2003), no significant difference in the number of fixations to the target zone would indicate the execution of a similar visual, but not necessarily motor, strategy between conditions. In addition, repeated fixations at the target would provide a measure of participants' engagement in the covert tasks (Heremans et al., 2008).

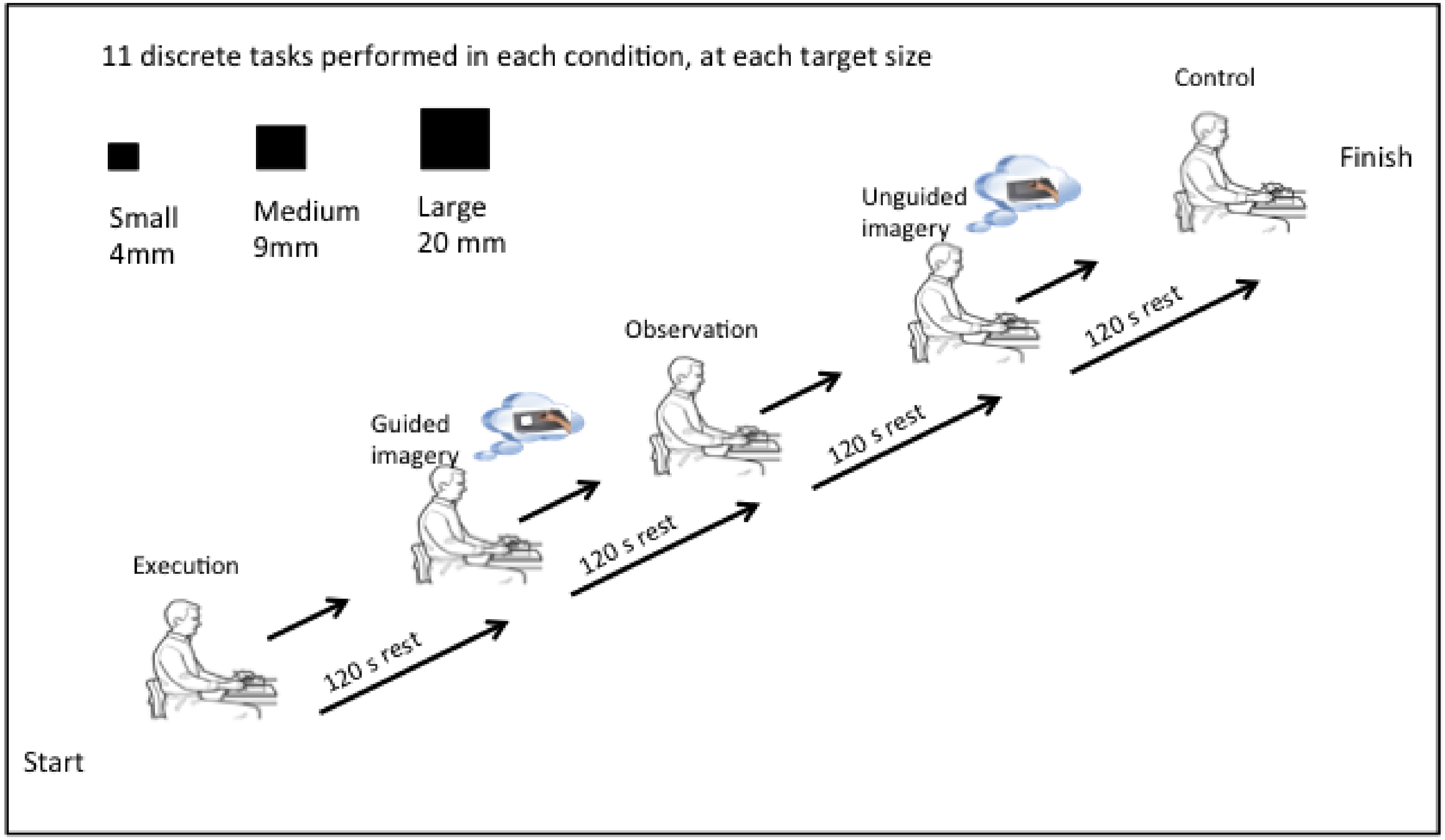


Figure 3-2: Experimental protocol for Study 1 (a similar protocol was also used in Study 2).

The control condition was also included in this analysis. The fixations in this condition were expected to be epiphenomenal rather than functional, and significantly different to that of the simulation states (Heremans et al., 2008).

Fixation duration

The total fixation duration at the target (per block of trials) was computed for each participant and compared between conditions. Comparable values for fixation duration, that were similarly influenced by task complexity, would provide evidence of a shared eye motor representation (Flanagan & Johansson, 2003).

Data analysis

The eye movement data were analysed using Gazetracker software (Lankford, 2000). All trials incurred < 5% loss in tracking time. The first trial in each block was discarded since pilot testing revealed MT in this trial to be more variable. Excluding the control condition, which was analysed at a block level, eye movements during 120 trials were analysed for each participant: 10 (trials per block) x 4 (conditions: AE, AO, GMI, UGMI) x 3 (target sizes: large, medium, small). The Shapiro-Wilks test were used to identify normal distribution and sphericity was assumed if Mauchly's test of sphericity was > 0.05. Effect sizes were calculated using partial eta squared values (η_p^2) and the alpha level for significance was set at 0.05. Pairwise comparisons were LSD corrected. All data are presented as means and Greenhouse-Geisser corrected.

3.3 Results

Chronometry measures

To confirm participant task compliance, MT was recorded and compared using a 3 (condition: AE, GMI, UGMI) x 3 (target size: large, medium, small) repeated measures (RM) ANOVA. Main effects were found for condition ($F_{1.403, 16.831} = 9.338$, $p = 0.004$, $\eta_p^2 = 0.438$, and target size ($F_{2, 24} = 3.793$, $p = 0.037$, $\eta_p^2 = 0.240$). There were no significant interactions. Pairwise comparisons revealed MT was significantly quicker in AE (2.681 s) when compared to GMI (3.106 s, $p = 0.046$) and UGMI (3.460 s, $p = 0.004$). MT was also significantly quicker in GMI compared to UGMI ($p = 0.008$). For target size, MT was significantly quicker for the large target (2.943 s) compared to the small target (3.207 s, $p = 0.028$) across all conditions. There was no significant difference between the large and medium targets (3.097 s, $p = 0.140$) or between the medium and small targets ($p = 0.215$).

Total number of fixations

A 5 (condition: AE, AO, GMI, UGMI, Control) x 3 (target size: large, medium, small) RM ANOVA was used to compare the total number of fixations at the target zone. A main effect was found for condition ($F_{4, 48} = 21.401$, $p < 0.001$ $\eta_p^2 = 0.641$, but not for size ($F_{2,24} = 1.527$, $p = 0.113$) and there were no interactions, (see Figure 3.3). Pairwise comparisons revealed that significantly more fixations were made during AE (15) compared to all other simulation states; AO (12, $p = 0.006$), GMI (12, $p = 0.003$), and UGMI (12, $p = 0.018$). There were no significant differences between the covert conditions.

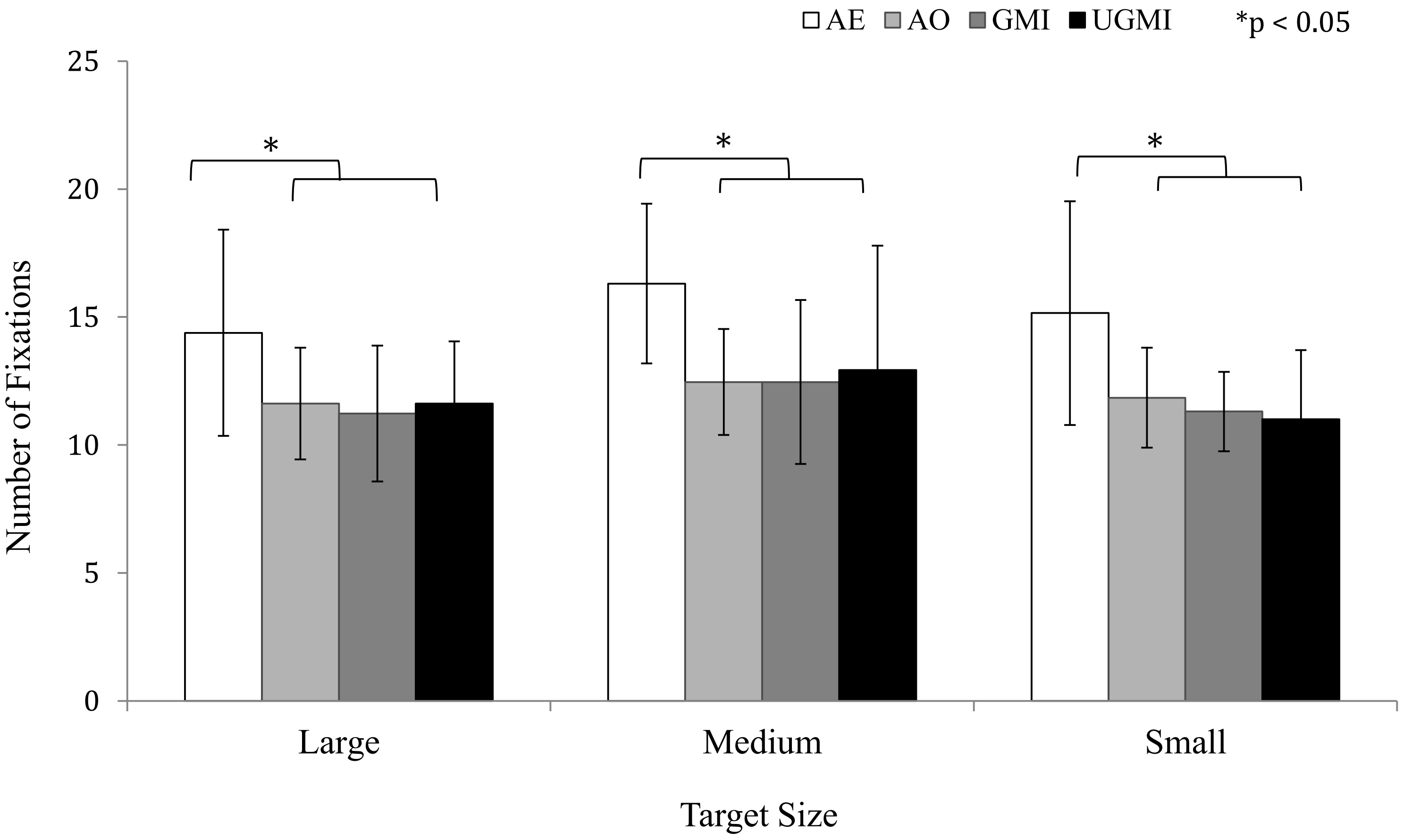


Figure 3-3: Total number of fixations at the target 'look-zone' over 10 consecutive trials for all series and conditions.

A control condition was included in this analysis to confirm that the fixations in the target zone were task related. Significantly fewer fixations (5, $p < 0.001$) were observed during Control compared to AE, AO, and GMI and UGMI. In addition, the number of fixations in this condition was highly variable as reflected in the large standard deviations (large target 7 ± 6, medium target 5 ± 4, small target 4 ± 5).

Total fixation duration

A 4 (condition: AE, AO, GMI, UGMI) x 3 (size: large, medium, small) RM ANOVA was used to compare total fixation duration. A main effect of size ($F_{2, 24} = 4.204$, $p = 0.027$, $\eta_p^2 = 0.259$), but not condition ($F_{1.603, 19.239} = 1.656$, $p = 0 .194$), was observed. There was also a significant size by condition interaction ($F_{6, 72} = 2.227$, $p = 0.050$, $\eta_p^2 = 0.157$; see Figure 3.4). Simple effect analyses revealed that in AE and AO the total fixation duration was significantly shorter for the large target size compared to the small target size (AE, 8.692 s vs 10.815 s, $p = 0.005$; AO, 7.447 vs 10.212 s, $p = 0.001$), and for the large target size compared to the medium target size (AE, 8.692 s vs 10.210 s, $p = 0.002$; AO, 7.447 s vs 9.115 s, $p = 0.054$). All other comparisons were not significant.

Manipulation checks

Participants completed the MIQ-RS to assess ease of imagery generation ability. All participants rated their ability as at least average. Mean scores of 33.82 ± 9.42 (VI) and 34.09 ± 8.56 (kinaesthetic imagery) were recorded. Manipulation checks were performed post experiment to examine the participants' MI and AO experiences of the reach and point task. For MI, mean scores revealed that the visual component of the imagery was considered at least 'somewhat easy to see' (GMI = 5.54 ± 1.13, UGMI = 5.47 ± 1.98).

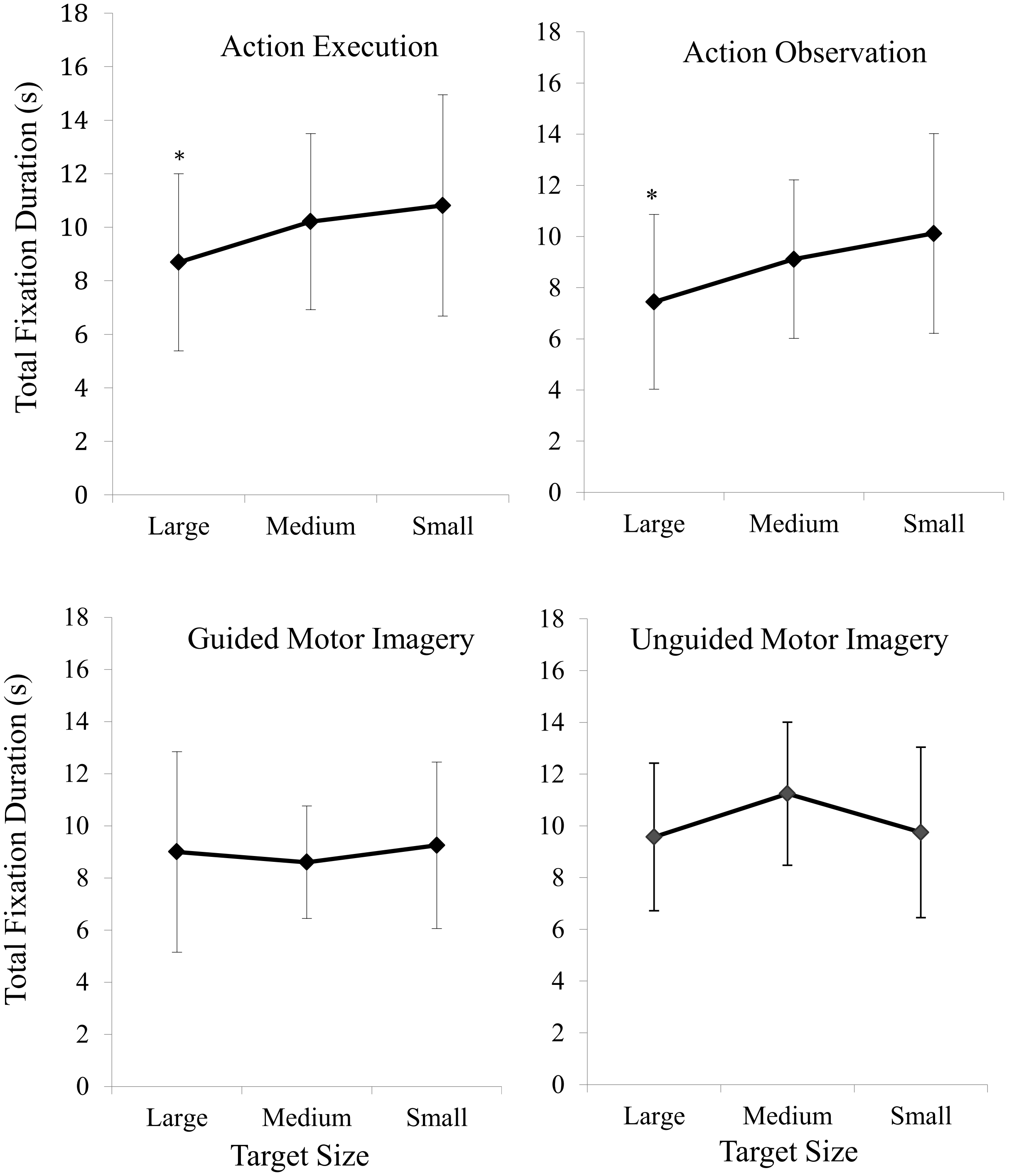


Figure 3-4: Total dwell time at the target during 10 consecutive trials, for all series and conditions. *Significantly different to Small target ($p < 0.05$).

Kinaesthetic imagery was rated as ‘somewhat hard to feel’ (GMI = 3.54 ± 1.11, UGMI = 3.08 ± 1.98). For AO, mean scores revealed that the visual component of the AO was considered at least ‘very easy to actively engage with’ (6.77 ± 0.60). The kinaesthesis component associated with AO was rated as ‘very hard to feel’ (1.46 ± 2.82).

3.4 Discussion

The current study explored eye gaze behaviour across four experimental conditions using a forward reach and point VFT. The hypotheses were partially supported: (i) MT was not strictly congruent between AE, GMI and UGMI conditions, but was similarly influenced by target size across all conditions; (ii) the number of target fixations was significantly different between AE and all covert conditions but all conditions were similarly influenced by target size; and (iii), total target fixation duration remained congruent in AE and AO and both conditions displayed an indirect Fitts’ Law effect. The findings suggest there are similarities in the fixation metrics and also some specific differences. Therefore, these data provide partial support for a common representation and Simulation Theory and, for the first time, through eye movement metrics. The discussion is organised by dependent variable.

Equivalence in chronometry measures

The MT in AE and MI was compared in three levels of task difficulty. In agreement with others (Decety et al., 1989; Maruff et al., 1999), MT was significantly quicker in AE compared to the GMI and UGMI conditions. Decety et al. (1989) reasoned that increased force in AE (required to maintain similar levels of performance in more effortful tasks) is interpreted as increased MT in MI (of the same task). In the current study, the participants were asked to perform all tasks optimally, focussing on both speed and accuracy. It was possible that increased effort was required to decelerate the limb and place it accurately and quickly at the medium and small targets during the current control phase of the movement (Abrams et al., 1990; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). This increase in effort could have been interpreted as an increase in time during MI. MT was also found to be significantly longer in UGMI compared to GMI. Kosslyn (1975) suggested that additional time is required in VI when the tasks are more complex. The data support this idea given that the UGMI condition required participants to generate and inspect additional images (i.e., the target). Some researchers have argued that overestimations in imagined MT can occur because tacit knowledge is used instead of MI (Pylyshyn, 1973). For example, the participant may count internally to direct the behaviour in an attempt to match the MT. If the participants had used tacit knowledge in the current study, MT should have been similar in both GMI and UGMI conditions. This was not observed since MT in GMI was significantly quicker compared to UGMI.

Fitts' Law has been demonstrated to constrain MI in a similar manner to AE (Decety et al., 1989; Maruff et al., 1999). In support of the findings of Maruff et al., MT in AE and MI was found to be significantly greater for the small, more complex target task compared to the medium and large, less complex target tasks. These data provide further support for the theory of a common motor representation that is accessed during MI and AE. In addition, the data confirm participants' engagement in both MI tasks.

Number of fixations

The control condition data indicated that the fixations performed during this task were epiphenomenal rather than functional. Participants demonstrated a variable eye movement pattern in this condition (evidenced through the large standard deviations) that was inconsistent with the other experimental conditions. These data provide support the idea that the eye movements were task related in the AE, AO, GMI and UGMI conditions.

There were significantly more fixations in AE compared to the covert conditions. The goal of the task was to point to a target as accurately and quickly as possible, in AE this included the coupling of two effectors, the limb and the eyes. During the AE of a pointing task an individual will typically produce anticipatory saccades to the target site before the limb arrives and remain there until the task is complete. Online comparison of the feedforward efferent motor command with visual and proprioceptive afferent feedback occurs to place the limb accurately at the target. If the placement of the first fixation provides incorrect or insufficient information, a corrective saccade and subsequent fixation occurs (Abrams et al., 1990). In contrast to AE, in the covert conditions no additional fixations related to error correction of the limb trajectory were required and hence the number of fixations was less in this conditions. The results contradict those of Heremans et al. (2009), who reported no significant difference in the number of fixations between AE and visually assisted MI; this may be due to differences in task complexity. In the Heremans et al. study, the relatively simple task involved a controlled cyclic wrist extension/flexion movement, whereas in the current study participants optimally performed (i.e., considered speed and accuracy) a gross motor movement. The findings highlight the fact that the neural overlap between conditions is not complete. For this metric, the covert conditions have no need, or appear unable, to simulate the fine adjustment of the motor representation that occurs in tasks that are guided by afferent feedback and sensory expectation.

The number of fixations in the target zone in the UGMI condition was consistent with the other more visually assisted conditions. During object related perception, spatial information is suggested to be encoded in a spatial index associated with eye movements. During memory retrieval or MI, the spatial representation is reported to be accessed by executing the same eye movements as perception (Heremans et al., 2008; Ryan & Villate, 2009; Spivey & Geng, 2001). In the current study, the UGMI condition provided no task relevant information except the stationary limb and the HOME button. Jeannerod (1986) proposed that in visuomotor tasks the motor representation is permanently fed with information from two sources, conceptualised as a visual map and a proprioceptive map. The visual map encodes the position of the target with respect to the body using retinal information; the proprioceptive map encodes the static and dynamic proprioceptive signals from the limb. It is possible that the stationary limb provided the motor representation with the necessary inputs to be able to re-execute the accurate landing position of the target fixation. Others have also demonstrated that MI can be facilitated if the limb is in a position that is congruent with the task demand (Lorey et al., 2009). These findings provide support for the PETTLEP approach to MI (Holmes & Collins, 2001).

In agreement with others (e.g., Abrams et al., 1990; Heremans et al., 2008), the number of fixations to the target was not influenced by task complexity (i.e., target width). The AE of simple aiming tasks typically requires no more than two fixations at the target in order to determine the target's location in the visuomotor workspace (Abrams et al.). A comparable fixation pattern was observed in this study and implies that the target location was optimally determined in all conditions. This suggests that in overt and covert conditions the number of fixations remains relatively robust to changes in task complexity, providing further evidence of a shared motor representation.

Total fixation duration

Fixation duration is reported to consist of three processes: visual field sampling; analysis of foveal information; and planning of the next saccade (Viviani, 1990). In the current study, visual field sampling was controlled using a privacy screen, and planning of the next saccade, after target acquisition, was controlled with the HOME button that was constant across trials. Consequently, it was inferred that any difference in fixation duration was due to the analysis of foveal information and the computation of the motor plan. In AE and AO the fixation duration was significantly influenced by target size; fixation duration was longer for the small compared to the large target. Similar findings have been reported by others during the AE of near aiming tasks (Williams et al., 2002). These data indicate that the information processing demand increased as a function of task complexity in AE and

AO, and this may reflect additional cognitive processes associated with pre-programming parameters (e.g., direction, force, and velocity) of the movement.

Some authors (e.g., Desmurget et al., 1999; Kourtis, Sebanz, & Knoblich, 2012; Mottet, Guiard, Ferrand, & Bootsma, 2001) suggest the scaling of the MT by task complexity is an emergent process; crude motor plans are formed during action preparation and continually updated during action performance. The online modulation of the motor output is achieved via the posterior parietal cortex that acts as a ‘neural comparator’, comparing eye signals (retinal and extra-retinal) to proprioceptive and efferent copy signals. In the current study, fixation duration was influenced by task complexity in AE and AO, but not in GMI or UGMI. This suggests that the amount of information processing was also an emergent process. It is possible that the internal, top down model used in MI is sufficient to generate crude motor plans (the MT was significantly different to AE but similarly influenced by task complexity) but is unable to simulate the dynamic feedback conditions. Other researchers (Heremans et al., 2009) have also reported no effect of task complexity on temporal fixation markers (e.g., the time between successive fixations) in cyclic aiming tasks. In contrast, and in agreement with others (Flanagan & Johansson, 2003), the similar and dynamic behaviour of fixation duration in AE and AO suggests the activation of an enhanced, dynamic motor representation that is shared by both conditions. These findings suggest that the sub-components of aiming tasks are processed differently in GMI and UGMI compared to AE and AO. These data corroborate the findings of Calmels et al. (2006) who reported that elite gymnasts, with medium – high MI ability, imagined a complex gymnastic routine in a temporally different format to that displayed in physical performance.

The lack of a main effect in fixation duration between conditions (with the target complexity data collapsed) appears to contrast with previous findings (McCormick et al., 2012). McCormick et al. (2012) reported fixation duration to be significantly longer in AO compared to MI conditions. These differences can be reconciled if the task designs are considered. In the McCormick et al. study, MT was fixed between the AO and MI conditions. In the present study, MT was self-determined during the MI conditions and shown to be significantly longer than AE (and by extension AO, since the video recording of AE was presented in AO). Therefore, in agreement with McCormick et al., this suggests the time spent fixating in MI, relative to MT, was less than the time spent fixating in AE and AO, relative to MT.

Imagery ability and manipulation checks

All participants had at least average kinaesthetic and VI skills. The manipulation checks revealed that participants found the kinaesthetic component of the MI more difficult to perform than the visual component. The ability to maintain the temporal preservation of the organisation of movement during MI has been taken as evidence of kinaesthetic imagery (Lotze & Zentgraf, 2010). The overestimation of MT in MI may be indicative of sub-optimal kinaesthetic imagery. In contrast, the spatial accuracy in MI, evidenced through repeated fixations in the target look-zone, corroborates the above average scores recorded during the VI assessment. The manipulation checks suggest that participants found it easier to engage in AO compared to MI. In AO there were no instructions to ‘feel’ the movement, instead participants were requested to ‘observe with the intent to imitate’. The low scores for kinaesthesis suggest that participants did not include this modality when performing

AO. Thus, it appears that the temporal preservation of the movement in AO, as evidenced through fixation duration, is achieved via mechanisms other than conscious limb kinaesthesis. This could be an eye motor representation that is shared in AE and AO.

Conclusion

Using a single experimental paradigm, eye movements were measured to test the predictions of Jeannerod’s Simulation Hypothesis. All participants fixated the target look-zone, indicating that similar information was attended to across conditions. Fixation duration was influenced by task complexity in AE and AO. This suggests that dynamic manipulation of the motor representation in response to task constraints occurs similarly in AE and AO but not MI. As such, AO may be a more effective technique in supporting complex motor processes. The close similarity between AE and AO may support the use of AO as a prime to MI, if chronic immobility has compromised effective physical movement (e.g., stroke). This research highlights the importance of considering the dynamic nature of the motor representation and its influence on behaviour in the covert conditions.

4 Study 2: The influence of early ageing on eye movements during motor simulation

4.1 Introduction

Covert training processes such as AO and MI are increasingly proposed as adjuncts to physical therapy during the motor rehabilitation of older individuals (Ertelt et al., 2007; Page et al., 2007). The use of MI and AO in these populations has, however, generally assumed that the motor simulation skills of older individuals are unaffected by age. In healthy ageing, efficient movement can be compromised through: modifications within the musculoskeletal system (Kinoshita & Francis, 1996; Narici & Maganaris, 2007); loss of sensorimotor and proprioceptive sensitivity (Klein, Rice, & Marsh, 2001; Leonard & Tremblay, 2007); a slowing in processing visual information (Briggs, Raz, & Marks, 1999); or, cognitive decline (Salthouse, 1996). If, as neurophysiological studies increasingly demonstrate, the motor representation is shared between overt and covert conditions, then any detrimental age related changes associated with AE might also reduce the effectiveness and efficacy of AO and MI.

The performance of overt and covert motor tasks is frequently compared using self-report inventories and brain mapping techniques. Although these are useful measures, the drawbacks with measures of neural activity has been previously discussed (see section 2.1.1) and self-reports rely on an individual's introspective access to conscious awareness (Collet, Guillot, Lebon, MacIntyre, & Moran, 2011). An alternative method, the chronometry paradigm, compares the time taken to perform and imagine a motor act, with similar MT taken as evidence of MI ability

(Guillot & Collet, 2005b). An important aspect of this temporal relationship between AE and MI is that if task complexity is increased then MT increases similarly in AE and MI (Decety et al., 1989). Thus both the physical and mental performance of action is similarly constrained by Fitts' Law (Fitts, 1954). Researchers frequently exploit this phenomenon and use MT as a manipulation check to ensure task compliance in the covert tasks (Gabbard, Cacola, & Bobbio, 2011; Heremans et al., 2011). The temporal correspondence between AE and MI is not suggested to develop until late adolescence, with proficiency achieved once the neural systems supporting internal modelling have matured (Caeyenberghs et al., 2009). Whilst older adults demonstrate temporal congruency (Sirigu et al., 1996), they may also underestimate (Personnier, Kubicki, Laroche, & Papaxanthis, 2010); and overestimate (Skoura, Personnier, Vinter, Pozzo, & Papaxanthis, 2008) the imagined MT. It is has been suggested that the temporal inconsistency may be related to the task as younger individuals have been reported to over-estimate the imagined duration when more complex tasks are performed (Guillot & Collet, 2005b). The temporal inconsistency may, however, also reflect age-related changes in the cognitive mechanisms mediating the relationship between physical and mental practice (Skoura et al., 2008). Measuring 'real time' cognitive processing, in addition to MT, may offer a more comprehensive method of comparing overt and covert performance in this age group. One method of achieving this is by measuring eye movements (Heremans et al., 2008; Moran, 2009)

Contemporary research has compared the cognitive organisation of an action in AE, AO, and MI through the measurement of visual fixations (for a review see Causer, McCormick, & Holmes, 2013). These specific gaze parameters have been extensively used by cognitive and sport psychologists to infer the focus of attention (Vickers, 2009). The number and spatial distribution of fixations is considered to reflect the visual information that an individual considers most important, the temporal distribution may be used to identify the relationship between the visual cues, and the duration is considered a measure of information processing demand (Zelinsky, 2013). In Chapter Three of this thesis, it was demonstrated that young adults attend the same visual cues in AE, AO, and MI but that the visual information processing demand is congruent between AE and AO only. These findings highlight the sensitivity of using this method and suggest that there are discrete differences as well as similarities in the cognitive organisation of overt and covert action, even in the absence of age related influences.

At present there appears no research that has used eye movements to compare the cognitive processes of healthy, older adults during AE, AO, and MI. In studies that have examined eye movements in AE, older adults are reported to need more time to extract and process the visual information and programme the appropriate motor responses (Di Fabio, Greany, & Zampieri, 2003; Sekuler et al., 2000). These changes in gaze behaviour may not always accompany changes in motor performance (Chapman & Hollands, 2006). Chapman and Hollands (2006) compared eye movements during gait in healthy older and younger adults and reported gaze differences even when comparable MTs were achieved. This suggests that age related changes in cognitive processes might occur in the absence of physical decline, or to compensate for physical decline. This potentially challenges the efficacy of using mental practices techniques such as AO and MI for motor (re)learning in older adults. To date, two published studies (Heremans, et al., 2012a; Heremans, et al., 2012b) have reported the eye movements of an older adult control group (> 60 years) during the AE and MI of a wrist flexion/extension task. In both studies, the number of fixations and inter-fixation amplitude was found to be congruent between the two conditions. Based on these findings Heremans et al. suggested that MI ability was preserved in older adult populations. Whilst the congruent eye movements do suggest cognitive organisation of the action was similar between AE and MI, the absence of a younger healthy control group makes it difficult to identify to what extent, if any, the performances were influenced by age-related changes.

Many have considered age-related changes to manifest from 60 years onwards (for a review see Salthouse, 1996). Supporting this assumption, numerous studies have demonstrated performance breakdown when extremes of the adult age continuum are compared young adults (20-25 years) and older adults (70+ years). While overt age-related changes in motor tasks (for example an increase in reaction time) may not be apparent until over the age of 60, to achieve comparable reaction times with young adults older adults have to invest additional cognitive effort (Chapman & Hollands, 2006; Seidler et al., 2010). Thus, the cognitive techniques used to compensate for age-related changes may mask the observable onset of age-related decline. In a recent review examining mental processes and ageing, Saimpont, Malouin, Tousignant, and Jackson (2013) provided evidence of age-related changes in participants of 55 years and older. Others (Rönnlund, Nyberg, Bäckman, & Nilsson, 2005) have also suggested that cognitive processes are relatively robust until the age of 55. These findings suggest it may be pertinent to investigate the influence of ageing in a slightly younger population than traditionally recruited.

The primary aim of this study was to compare the AE, AO, and MI of upper limb movement between healthy young and early ageing adults. Specific eye movements provided the primary dependent variables and additional measures (MT and self-reports) were used to triangulate the data and confirm participant compliance in the covert tasks. Based on the findings of others (Flanagan & Johansson, 2003; Heremans et al., 2012a), and the concept of shared neural networks in motor simulation (Jeannerod, 2001) it was hypothesised that the gaze strategy executed in AE would be preserved in MI and AO. It was expected the MT would be influenced by target size and, due to age related slowing, be increased in the older group. Based on the conflicting findings to date, no predications were made regarding whether the MT in MI would increase or decrease compared to AE.

4.2 Methods

A sample of 16 healthy participants was split equally into two age groups, old (mean age = 59 ± 7 years, 7 females) and young (mean age 30 ± 11 years, 7 females). Prior to testing it was confirmed that all participants: had normal or corrected to normal vision; were righted handed (old group = 94.75 ± 4.35; young group = 95.80 ± 4.85 years; EHI; Oldfield, 1971); had at least average MI ability (old group, VI = 34.63 ± 6.37, kinaesthetic imagery = 33.25 ± 10.01; young group, VI = 31.88 ± 10.35, kinaesthetic imagery = 34.25 ± 5.23; MIQ-RS; Gregg et al., 2010). Two participants in the older group were retired but still physically active, reporting cumulative walking of at least 60 minutes each day. The remaining participants were office workers or similar. All participants were naïve to the hypotheses being tested and provided written consent to take part. The protocol were approved by a

Departmental Ethics Committee at the Manchester Metropolitan University and conducted in accordance with the Declaration of Helsinki.

Experimental procedure

The experimental protocol is very similar to that used in Chapter Three (Study 1). As a comprehensive description and rational of the methods section is given in section 3.2 (page 57), only a brief overview is reported here.

Measures

The MIQ-RS (Gregg et al., 2010; see Appendix B) was administered to measure MI ability. Following the recommendation of others (Fourkas, Ionta, & Aglioti, 2006; Goginsky & Collins, 1996), an in-house questionnaire (see Appendix D) was also administered post-experiment to subjectively assess participants' MI and AO performance.

Eye movements were recorded using an Applied Science Laboratories (ASL) Mobile Eye system (Bedford, Massachusetts). A fixation was defined as a stable gaze position (i.e., within 0.67 ° visual angle) that was maintained for at least 120 ms. Pilot testing of the task revealed no significant horizontal eye movements and therefore only vertical gaze was analysed. 'Look-zones', areas equivalent to the target size plus a tolerance: large target = 6 mm^2; medium target = 7 mm^2; small target = 8 mm^2; were determined during pilot testing and reflected the area most heavily populated by fixations during the current control phase of the physical movement. The tolerance accommodated for drift, compressions, expansions and individual gaze behaviour preference (Laeng & Teodorescu, 2002). The look-zones were overlaid onto each target during post processing and all fixations within these zones were analysed. To eliminate experimenter distraction, the equipment was operated from outside the testing booth. A chin rest was used to restrict head movements and participants were requested to refrain from talking whenever possible. The equipment was calibrated immediately prior to the experiment using a 9 point grid which was presented on the tablet once the participants were seated appropriated.

Goal directed movement task

The VFT was used to examine the internal model associated with the motor planning processes involved in AE, AO and MI. The task was performed using a calibrated (pre-experiment) tablet (ST2220T, Dell United Kingdom Inc.) and a hand held stylus (normal pen size and weight). The experiment was hosted in DMDX (Forster & Forster, 2003) to precisely control the timing and presentation of participant instructions and the action related stimuli. Participants held the stylus in their right hand and performed the VFT in three conditions: (i) AE; (ii) MI; and (iii) AO. In all conditions a HOME and FINISH button together with a TARGET square were presented on the tablet (see Figure 3.1). The HOME and FINISH buttons were positioned approximately 200 mm away from the participant's torso (midline). The TARGET was vertically aligned with the HOME button and the amplitude between the closest edges of the HOME and TARGET was constant (185 mm). Three TARGET squares of different sizes were used: large (20 mm^2), medium (9 mm^2), and small (4 mm^2). The different TARGETs led to task IDs of 4.2, 5.4 and 6.5 respectively (ID = log2 (2A/W), Fitts, 1954).

Note: Unlike Study1, the UGMI condition was excluded from this study to reduce the experimental demands on the older individuals. Aside from the different age groups, this is the only aspect of the experimental protocol that differs between Study 1 and Study 2.

In AE and MI, the HOME button was tapped to begin the task. In AE, participants physically moved the stylus to the TARGET, back to HOME and then to FINISH. In MI, the same action was imagined but without any concomitant movement to the TARGET button. The MT, the time from when the stylus left the HOME button until it pressed the FINISH button, was recorded in both AE and MI. In AO, the participants held the stylus and observed the previously recorded video of their movement.

Control

To ensure that the eye movements in the simulation conditions did not reflect random oculomotor behaviour a control condition was included. In this condition the TARGET, HOME and FINISH buttons were presented on the tablet and participants were instructed to count back slowly from 100. After 60 s (a time equivalent to the mean time spent performing a complete block of repeated tasks in AE) the participants were asked to rest. To ensure a maximally homogeneous task across all participants a series of instructions were issued. In AE, participants were requested ‘to move the stylus as quickly as possible but not to risk improving speed at the expense of accuracy’. They were also informed that ‘two or more false starts or target misses during any block would result in that block being restarted’. In MI, participants were instructed to use MI from a first person egocentric, visual orientation. To control the MI, a brief script was recited by the experimenter which described the scenario and the imager's inner response to the scenario (Lang, 1979): 'see yourself accurately reach the square target, as if you were actually performing the movement' and 'feel your grip on the stylus, feel the muscles in your upper arm contract, feel your arm extend as you perform the movement'. Participants were requested to refrain from any upper limb movement in this condition. In AO, the participants were instructed to remain stationary and to 'observe the action with the intention to imitate it at a later time'.

Experimental procedure

Participants were fitted with the eye tracking system and initially performed a single habituation block of the VFT using a target that was a different size (15 mm^2) to the experimental tasks. Participants were then assigned to one of three starting series defined by target size (large, medium, small). Each series began with one block (11 repeated reach tasks) of AE, followed by one block of each of the other conditions, i.e. MI, AO, and Control, counterbalanced (see Figure 3.2). Each block consisted of 11 repetitions of the task followed by a 120 s rest. Following each rest period the calibration of the Mobile Eye was checked. At the end of the experiment each participant was debriefed fully and manipulation checks were performed to confirm participant compliance in the covert tasks.

Gaze analysis

The number of fixations and total fixation duration of the fixations located within the look-zones was computed. In addition, the inter-fixation distance, calculated as the distance of the location of the first fixation from the HOME button following task onset was also computed. The first trial in each block was discarded since pilot testing revealed MT in this trial to be more variable. In total, the data reflected 1440 trials: 16 (participants) x 3 (conditions; AE, AO and MI) x 3 (target size; large, medium, small) x 10 (task repetitions per block). For the gaze metrics, the mean values per block were determined and used in the statistical analysis. The data in the control conditions represented performance at a block level and therefore 144 trials were analysed: 16 (participants) x 3 (conditions; AE, AO and MI) x 3 (target sizes; large, medium, small).

Statistical analysis

To confirm participant compliance during MI, MTs were compared using a 2 (condition: AE, MI) x 3 (target size: large, medium, small) x 2 (age: young, old) RM ANOVA. The temporal correspondence between AE and MI was further examined by calculating the within subject correlation coefficient (Bland & Altman, 1995, see explanation below). The total number of fixations was analysed using a 4 (condition: AE, MI, AO, control) x 3 (target size) x 2 (age) RM ANOVA. The control condition was included in this analysis to compare fixations in task related and task unrelated conditions. The differences in fixation duration were compared using a 3 (condition: AE, MI, AO) x 3 (target size) x 2 (age) RM ANOVA. The temporal correspondence of this metric between AE and AO, and AE and MI was further examined by calculating the within subject correlation coefficient (Bland & Altman 1995, see explanation below). To complete the analysis the primary inter-fixation distance was also compared using a 3 (condition: AE, MI, AO) x 2 (size: large, small) x 2 (age) RM AVOVA. This gaze parameter is particular susceptible to task strategy, and controlling task strategy in aiming tasks, irrespective of task instructions, can be problematic (Gesierich, Bruzzo, Ottoboni, & Finos, 2008). Under conditions of low ID, individuals tend to adopt a strategy that focuses on speed, but under conditions of high ID they may adopt a strategy that focuses on accuracy (Lazzari, Mottet, & Vercher, 2009). As the size of the medium target was not vastly different to either the large or small target, the focus of the strategy could have been either speed or accuracy. The medium target was therefore excluded from the analysis to remove any confound related to task strategy. Note: The correlation coefficients for MT and fixation duration were calculated using the method proposed by Bland and Altman for repeated observations. This type of analysis was used to determine if an increase in the temporal dependent variables (MT and fixation duration) in AO or MI was associated with an increase in AE. To calculate the correlation coefficients for repeated observations the variances between subjects are removed and only the changes within subjects are examined. Bland and Altman caution that treating data from repeated observations as a simple sample may mask a true relationship or result in a relationship being incorrectly identified.

The Shapiro-Wilks and Levene's tests were used to identify normal distribution and equivalent variance. Sphericity was assumed if Mauchly's test of sphericity was > 0.05. Effect sizes were calculated using partial eta squared values (η_p^2) and the alpha level for significance was set at 0.05. Pairwise comparisons were Bonferroni corrected. All data are presented as means and, where appropriate, Greenhouse-Geisser corrected.

4.3 Results

All participants complied with the task requirements. Task noncompliance accounted for 16 trials (2%) being retaken for the young group and 20 trials (3 %) being retaken for the older group.

Chronometry measures

Main effects were found for condition ($F_{1,\,14} = 4.649$, $p = 0.049$, $\eta_p^2 = 0.249$), target size ($F_{2,\,28} = 4.272$, $p = 0.024$, $\eta_p^2 = 0.234$) and age ($F_{1,14} = 5.694$, $p = 0.032$, $\eta_p^2 = 0.289$). There were no significant interactions. Pairwise comparisons revealed MT was slower in MI (2.976 ± 0.993 s) compared to AE (2.538 ± 0.798 s). For target size, MT was quicker for the large target (2.571 ± 0.812 s) compared to the small target (2.887 ± 0.895 s, $p = 0.035$). Older participants took significantly longer to perform the task (3.178 ± 0.925 s) compared to younger participants (2.335 ± 0.801 s) and, based on Cohen's guidelines (Cohen, 1988), exhibited weaker within subject correlations between AE and MI; a statistically significant within subject correlation was found for the young group ($r = 0.478$, $p < 0.05$) and for the older group ($r = 0.258$, $p = 0.037$; see Figure 4.1).

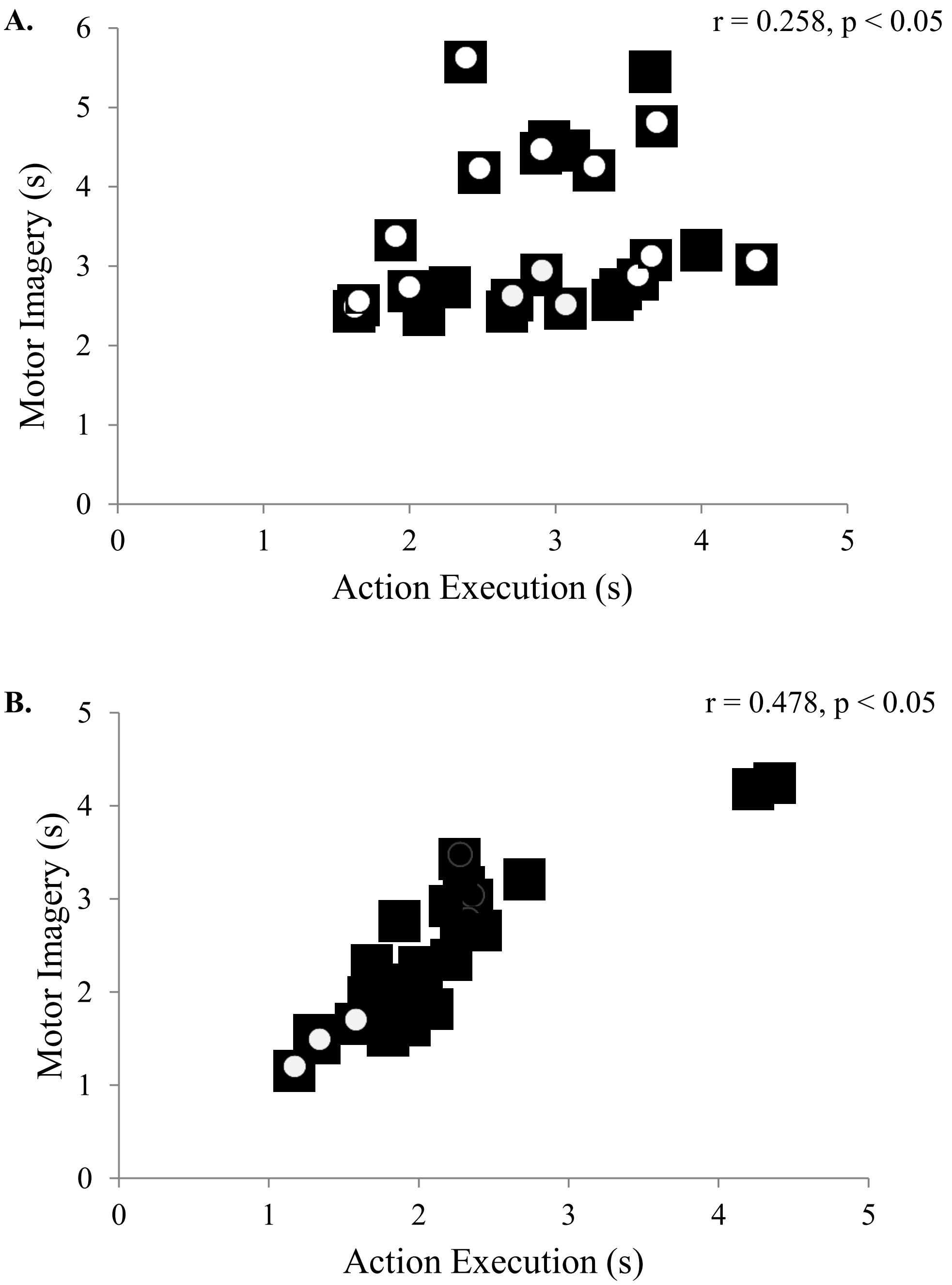


Figure 4-1: MT in MI plotted against MT in AE for the older adults (A) and young adults (B). Each point represents the mean MT of 10 repetitions to each target for each participant. Significant correlations were found for older and younger adults. See text (*Statistical analysis*) for further explanation.

Total number of fixations

There was a main effect for condition ($F_{1.872, 26.211} = 29.811$, $p < 0.001$, $\eta_p^2 = 0.680$), but not size ($p = 0.366$) or age ($p = 0.310$). Significantly more fixations were made in AE compared to all other states. There was a significant condition by age interaction ($F_{1.872, 26.211} = 4.342$, $p = 0.026$, $\eta_p^2 = 0.237$) and a significant condition by size interaction ($F_{2.704, 37.862} = 3.427$, $p = 0.030$, $\eta_p^2 = 0.197$; see Figure 4.2). Regarding the condition by age interaction, pairwise comparisons revealed that older individuals made more fixations in AE (17 ± 4) compared to AO (13 ± 3, $p = 0.006$), MI (13 ± 4, $p = 0.029$) and control (4 ± 5, $p = < 0.001$). Older participants also made significantly more fixations in AE compared to the younger group (13 ± 3, $p = 0.019$). For younger participants there was no significant difference in the number of fixations between conditions: AE (13 ± 3), AO (11 ± 2) and MI (12 ± 2) but significantly fewer fixations were observed in control (6 ± 7, $p = 0.045$). The number of fixations made during AO and MI was not significantly different between groups. The condition by size interaction revealed that more fixations were made to the large target (6 ± 6) compared to the medium target (4 ± 7, $p = 0.043$) in the control condition only.

Total fixation duration

A main effect for size ($F_{1.339, 18.742} = 9.734$, $p = 0.003$, $\eta_p^2 = 0.410$) but not condition ($F_{1.356, 18.981} = 1.239$, $p = 0.305$) was found. Pairwise comparisons revealed that the total fixation duration was significantly less at the large target (7.968 ± 3.250 s) compared to the small target (10.010 ± 3.903 s; Figure 4.3).

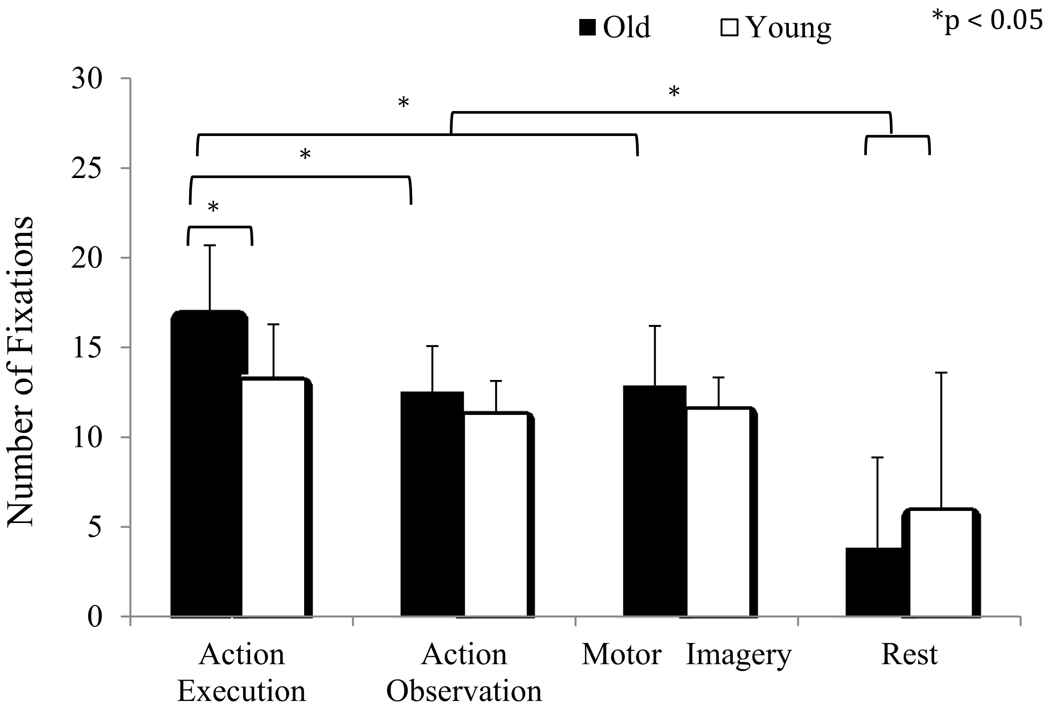


Figure 4-2: Mean number of fixations within the target look-zone based on 10 reach actions (data are collapsed for target size).

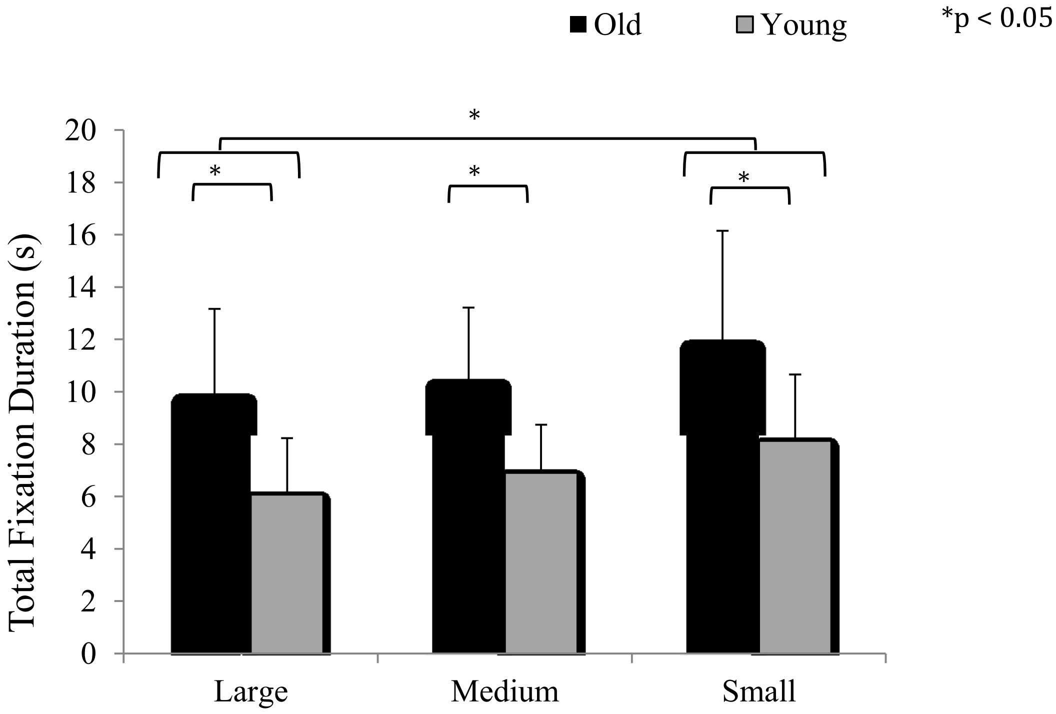
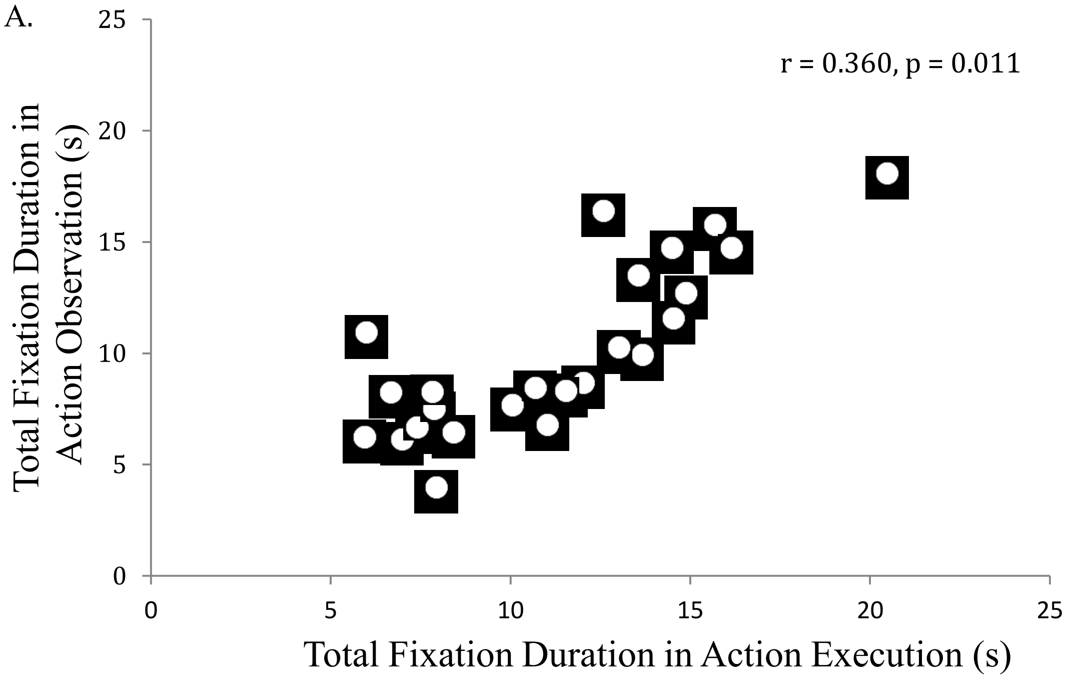


Figure 4-3: Total fixation duration during each block of 10 reach actions. Data are collapsed for condition as AE, AO, and MI were not significantly different.

There was a main effect of age ($F_{1, 14}$= 7.351, p = 0.017, η_p^2 = 0.344) that indicated older participants, compared to younger participants, fixated the target look-zone for longer (10.721 ± 3.115 s vs 7.040 ± 1.910 s). The fixation duration correlations between AE and AO, and AE and MI are illustrated in Figure 4.4. There was a significantly medium-large correlation between AE and AO for the young (r = 0.447, p = 0.006) and older (r = 0.360, p = 0.011) group. The correlations between AE and MI were not significant and have been omitted.

Inter-fixation distance

The RM ANOVA revealed a significant size by age interaction ($F_{1,14}$ = 5.465, p = 0.035, η_p^2 = 0.281; see Figure 4.5). Simple effect analyses revealed the inter-fixation distance was greater to the large target (175.323 ± 29.918 mm) compared to the small target (159.914 ± 38.311 mm, p = 0.019) for the younger participants only. There were no significant main effects.



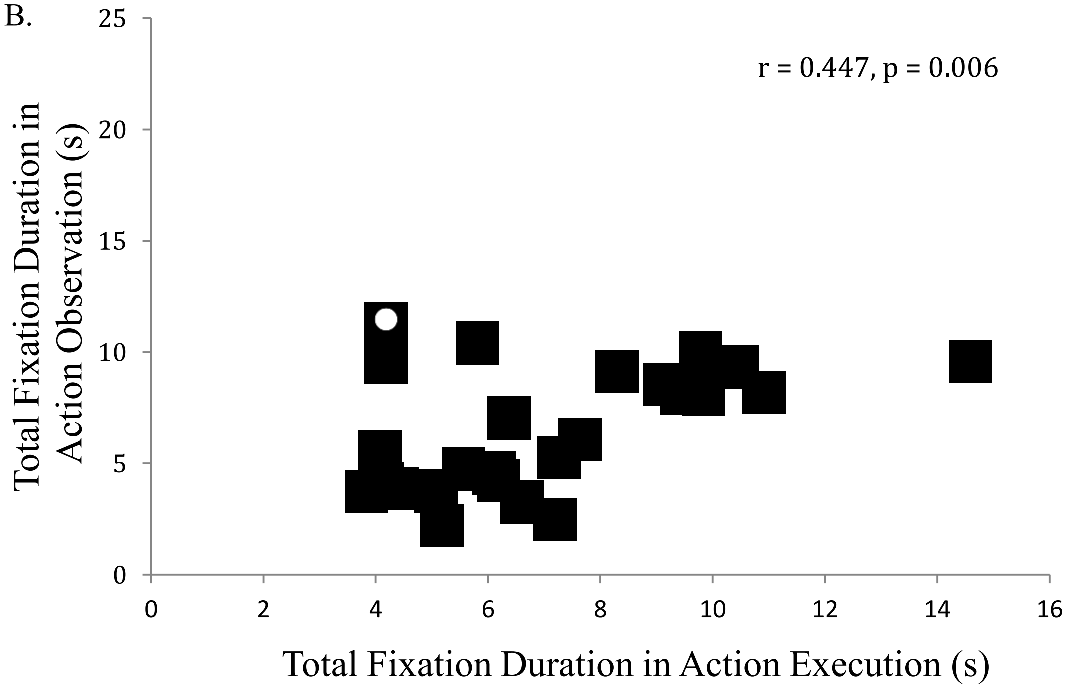


Figure 4-4: Fixation duration in AE plotted against AO for the older group (A) and younger group (B). Each point represents the total target fixation duration during 10 reach actions for each participant.

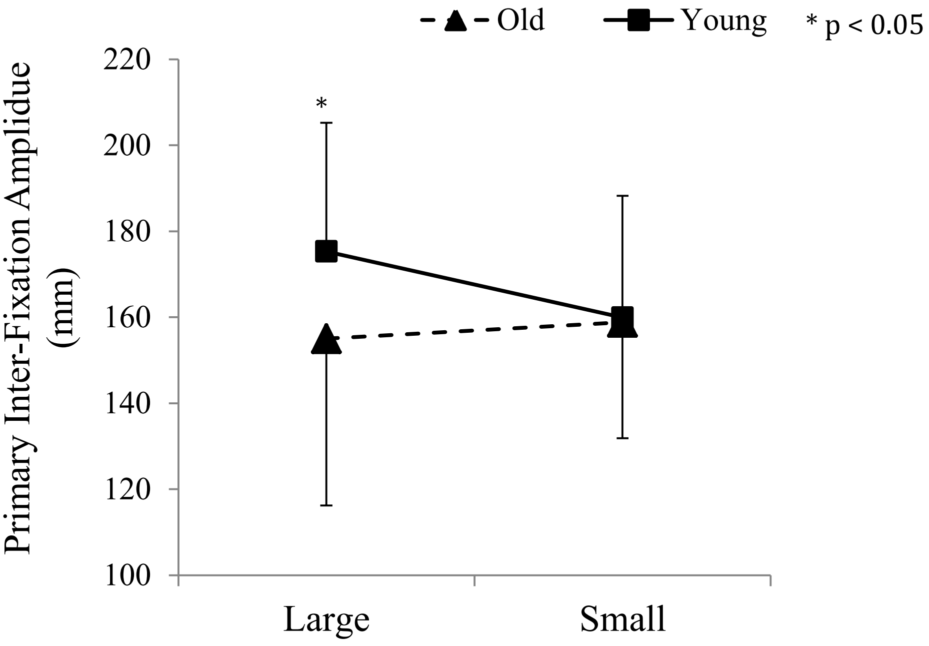


Figure 4-5: Primary inter-fixation amplitude per group. The * indicates a significant difference in the amplitude between target sizes for the young group only.

Manipulation checks

Manipulation checks were completed post experiment to assess participants' covert performance. In the older group, the visual component of MI was rated as 'somewhat easy to see' (5.500 ± 1.195), and the kinaesthetic component as 'somewhat hard to feel' (3.500 ± 1.773). In AO, the visual component was rated as 'very easy to engage in' (6.750 ± 0.707), and the kinaesthetic component as 'very hard to feel' (1.500 ± 2.828). In the younger group, the visual component of MI was rated as 'easy to see' (5.625 ± 1.302), and the kinaesthetic component as 'somewhat easy to feel' (4.625 ± 1.408). In AO, the visual component was rated as 'very easy to engage in' (7.000 ± 0.000, no variability in rated score), and the kinaesthetic component as ‘neutral (not easy or hard)’ (4.00 ± 2.928). Participants preferred to perform AO compared to MI. 87.50% (7 participants) of the older group, and 75% (6 participants) of the younger group perferred this simulation condition.

4.4 Discussion

Eye movements were measured in young and older adults to examine the influence of age on cognitive processes during the AE, AO, and MI of a goal directed action. The discussion is organised by dependent variable and self-reports have been included to supplement the findings. The chronometry data are discussed initially as this performance measure informs the interpretation of the data for the primary dependent variables.

Chronometry measures

The chronometry results indicated that all participants complied with the task. As hypothesised, older individuals took significantly longer to physically execute the tasks, however in both age groups the MT in AE and MI increased with target complexity. In both age groups the MT in MI was longer than the MT in AE and this may reflect the high degree of accuracy associated with the task (Guillot & Collet, 2005a). This group-wide increase in mental MT does not necessarily indicate impairment, but may reflect the different time constants of each condition. In MI the agent has to manipulate the image consciously (i.e., generate, inspect, maintain, and transform the image; Dror & Kosslyn, 1994) and this is predicted to introduce an additional time cost (Jeannerod, 1997).

The temporal relationship between AE and MI was weaker in the older group indicating a potential MI inaccuracy. MT is considered to be derived, in part, from muscular force, proposed to be part of the coded motor representation (Jeannerod, 1997). As there was no overt movement in MI there was no limb or object upon which to exert the planned force. Consequently, the level of force encoded in the motor command may have manifest as time in the covert states; increases in felt force represented as increases in time (Decety et al., 1989). The inability of the older group to accurately represent MT in MI may, therefore, reflect a reduced ability to accurately predict muscular force as a result of a decline in sensorimotor control and a modified musculoskeletal system. In AE, this reduced ability may be counteracted by a greater reliance on proprioceptive and online visual feedback, which is partially absent in the MI condition (Chapman & Hollands, 2006; Klein et al., 2001). The self-report data also appear to support these findings with older individuals rating the kinaesthetic component of their MI as ‘somewhat hard to feel’ in comparison to the younger group who rated it as ‘somewhat easy to feel’. In addition, given that MI is primarily a top-down process, the weaker temporal relationship could also be explained by an age related decline in cognitive function (Seidler et al., 2010). In support of this suggestion some, but not all, MI processes, such as the generation and maintenance of an image, are reported to become impaired with age (Dror & Kosslyn, 1994).

Number of fixations

Older participants made more fixations during AE compared to the younger group. The increase in the number of fixations suggests that the gaze strategy was less economical in this condition (Vickers, 1996). The chronometry data would support this interpretation given that the older group also took longer when performing the task physically. Goggin and Meeuwsen (1992) suggest that older individuals place a greater emphasis on the posture phase of a pointing movement in order to maintain task accuracy. Since no difference was observed in gross endpoint error between the younger and older group, it is possible that the older participants invested more effort in this component of the task to maintain performance. The reinvestment of effort in this manner would be supported by Attentional Control Theory (Eysenck, Derakshan, Santos, & Calvo, 2007). Given that the hands and eyes are reported to be tightly coupled (Helsen, Elliott, Starkes, & Ricker, 1998) it is possible that the additional fixations made by the older group represent the investment of this additional effort (Seidler et al., 2010).

In contrast to the study's hypothesis, the additional fixations executed during AE in the older group were not represented in the covert states. In MI and AO, fixations were fewer and similar in number to that of the younger group. These findings suggest that all participants adopted a similar gaze strategy in the covert conditions and both groups were equally proficient at the task. During AE, a crude feed-forward motor plan is generated and subsequently modulated by an error signal (the difference between the anticipated and actual position of the limb) determined through sensory feedback mechanisms (Desmurget & Grafton, 2000). In the covert conditions the feedback is significantly limited and therefore the magnitude of the error signal maybe insufficient to modulate the motor plan. In these conditions the simulated action appears to be based only on the initial feed-forward motor plan; in all trials there was at least one fixation to the target location to assist in coding the coordinates of the movement trajectory. This explanation would support the earlier interpretation that the additional fixations observed during AE in the older group were related to the error correction phase concerned with stabilizing the hand at the target (Ghez, Scheidt, & Heijink, 2007). Indeed, direct evidence from studies of primate motor cortex suggests that the posture and movement phase of a reach action involve distinct processes (Kurtzer, Herter, & Scott, 2005). A dissociation between the reach and grasp components of upper limb actions has been proposed (Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Jeannerod, 1997) and some authors (Edwards, Humphreys, & Castiello, 2003) report that in reach and grasp actions, the grasp component remains relatively robust to AO priming. The data from this study support these claims by demonstrating different gaze strategies during the sub components of the task in the covert conditions.

Some of these findings may appear to contrast with others. For example, Heremans et al. (2012a) reported no differences in the number and location of eye movements made by a healthy, older control group during AE and MI. Differences in task demand may explain these conflicting findings. The Heremans et al. study required participants to physically and mentally perform a cyclic horizontal wrist flexion/extension action between two targets at two different indices of difficulty (4.5 and 5.3), at rate of 0.5 Hz. This may be considered as a less demanding task compared to the present study where participants were requested to execute the task as quickly as possible while maintaining accuracy. In support of this claim, in the Heremans et al. study the participants typically made one eye movement per wrist movement during AE. This suggests that the initial feed forward motor plan may have been sufficient to guide a relatively simple task that involved little error correction. Given the earlier interpretation of the results, a similarity in the number of fixations during overt and covert movement would be expected. For both age groups, the number of fixations within the look-zones was not influenced by target complexity, suggesting that task demand was compensated by other gaze behaviour. Similar findings have been reported by others (Heremans et al., 2012a), and were also demonstrated in Study 1 of this thesis.

Collectively, these data suggest that motor simulation in MI and AO may offer older individuals movement practice conditions that are not constrained by age-related decline. Of particular importance to practitioners is that covert states do not appear to interpret the fine motor error corrections. The accuracy of the initial target fixation may, therefore, be critical to optimizing the mental practice benefits.

Fixation duration

Fixation duration was influenced similarly across all conditions supporting the concept of shared neural substrate. Compared to younger individuals, older adults fixated for longer but displayed relatively similar increases in fixation duration with increases in target complexity. The longer fixation duration may be a result of age-related slowness associated with processing the visual information (Briggs et al., 1999) or, in AE and AO, it may be related to a delay in the arrival of the hand at the target due to functional loss (Kinoshita & Francis, 1996).

The correlational data suggest that the congruency of fixation duration was enhanced between AE and AO in both groups. These data imply that the factors influencing the temporal allocation of an individual's attention in AE influenced attention in AO similarly. The self-report data support this interpretation given that

AO was rated as ‘very easy to engage in’ by both the older and younger groups, whereas the visual dimension of MI was given a lower rating, either ‘somewhat easy to see’ by the older group or ‘easy to see’ by the younger group. In addition, 88 % of older adults and 75 % of younger adults reported a preference for AO in comparison to MI. Collectively, the findings suggest that older individuals perform better at, and prefer, AO. The temporal congruency between AE and AO, and the preference for using AO, may be due to the common augmented feedback in these conditions. During AE and AO, the eye gaze strategy has been reported to work on a ‘just in time’ basis, where visual information is acquired and interpreted just at the point where it is required in the task (Flanagan & Johansson, 2003; Hayhoe & Ballard, 2005). This strategy is suggested to be employed to minimise the load on short-term memory (Ballard, Hayhoe, & Pelz, 1995). In contrast, in MI there is no augmented feedback and the image is the interpretation (Pylyshyn, 2003). Thus, the fixation duration (the time spent dwelling on a particular visual cue) is tightly governed by the evolution of the action in AO (as it is in AE), but is decoupled from the online action in MI. It is possible that under dynamic conditions individuals prefer using AO because it involves a more familiar and economic eye gaze strategy (Pylyshyn, 2000).

A factor contributing to the reduced congruency in the fixation duration between AE and MI may be attentional focus. During the AE and AO of near aiming tasks, individuals typically attend to the effect of an action rather than the limb movement required to achieve the action: they adopt a predictive, external attentional focus (Flanagan & Johansson, 2003; Williams et al., 2002). Attending to the moving limb is encouraged in acute movement rehabilitation, however, outside of this setting it may be detrimental to task performance (Hagemann et al., 2006; McNevin, Wulf, &

Carlson, 2000). In accordance with Langian theory (Lang, 1979), MI was facilitated in this study by including specific visual and kinaesthetic statements, referred to as stimulus and response propositions. It is possible, therefore, that the kinaesthetic response proposition ‘feel the muscles in your upper arm contract, feel your arm extend as you perform the movement’ encouraged a more internal, specific attentional focus than the external, general focus adopted during overt movement. Indeed, other researchers (Calmels et al., 2006) have also reported that conscious kinaesthetic sensations in MI (sensations that are typically absent during AE) cause a temporal discrepancy between AE and MI. These findings begin to highlight the multifarious influences on MI and the importance of the delivery instructions. Understanding how to control but not constrain MI for effective therapeutic use should be explored in future research.

Taken together these findings demonstrate that although older adults fixate for longer, their visual information processing behaviour is influenced in a manner similar to younger adults. There is some indirect evidence of neural sharedness across conditions (all conditions were influenced by target size), however the enhanced congruency between AO and AE suggests that dynamic, rather than static, visual cues activate additional shared processes in these conditions. In view of these findings, including dynamic visual cues in MI or performing MI simultaneously with AO, may support a more effective gaze strategy may enhance the efficacy of MI as a movement practice tool (Vogt, Rienzo, Collet, Collins, & Guillot, 2013). A similar approach of using augmented visual feedback to correct suboptimal gaze during AE has been demonstrated in the sports and clinical domains (Crowdy, Kaur-Mann, Cooper, Mansfield, Offord, & Marple-Horvat, 2002; Hagemann et al., 2006; Harle & Vickers, 2001).

Primary inter-fixation distance

The amplitude of the primary eye movement is considered to reflect the unmodified motor representation and is one of the first movements to be executed once a motor action has been programmed (Abrams et al., 1990). In this study, the primary inter-fixation distance was differentiated by target size in the young group only. Specifically, increases in the primary inter-fixation distance accompanied decreases in task complexity in AE, AO, and MI. This suggests that the younger group generated a motor representation based on task constraints. In contrast, the primary inter-fixation distance was not differenced by target size in the older group and this suggests that these individuals were either unable to modulate the amplitude, perhaps through functional loss, or executed a more conservative amplitude as a compensation mechanism.

In relation to the first suggestion, hypometric saccades (smaller eye movement amplitudes) are reported to occur in senescence (Huaman & Sharpe, 1993; Irving, Steinbach, Lillakas, Babu, & Hutchings, 2006). In this study however, the mean amplitude of the primary inter-fixation distance executed by the younger adults was within the range reported to still be achievable by healthy older adults. Furthermore, Heremans et al., (2012a) reported that a healthy, older adult control group adapted their primary inter-fixation distance to different target distances in a horizontal aiming task. It therefore seems unlikely that the older adults in this study were unable to voluntary adjust the amplitude to reflect the target complexity. A more likely explanation is that amplitude was constrained in the large target task as a compensation mechanism. The hand movement amplitude of older adults is suggested to behave differently to that of younger adults. The relative distance travelled in the primary sub-movement is reported to be substantially less in older adults, with the movement highly influenced by accuracy constraints (Ketcham, Seidler, Van Gemmert, & Stelmach, 2002). Altered muscle activation patterns and deficits in force modulation have been cited as possible causes for these age-related changes (Darling, Cooke, & Brown, 1989). Given that hand movement amplitude is suggested to be closely coupled with eye movement amplitude (Cotti, Guillaume, Alahyane, Pelisson, & Vercher, 2007), the conservative primary inter-fixation distance may assist the suboptimal hand movements by providing greater control during the terminal phase of the movement. Chapman and Hollands (2006) suggested that the central nervous system of older adults requires additional time to pre-plan movement and, to compensate for this, they adopt a less than optimal gaze strategy the prioritises the movement planning over online control.

The eye movement amplitude adopted by each group in AE was preserved in AO and MI. This pre-programmed part of the movement therefore appears embedded within the motor representation and, as such, may lend itself well to correction through cognitive intervention. Cotti et al. (2007) demonstrated that the adaptation of voluntary saccades (eye movement amplitudes) to targets generalises to hand pointing movements, specifically the amplitude of the hand movement increases with the amplitude of the saccade. If this is true then executing larger saccades (i.e., increasing the eye movement amplitude) during the AO and MI of reach movements may offer opportunities to correct the AE of these tasks in older individuals. Indeed, in the sports domain, cognitive interventions that involve the retraining of visual search strategies have been demonstrated to improve the biomechanics in far aiming tasks (Harle & Vickers, 2001).

Control

For both groups, there were significantly fewer fixations to the target look-zone during the control condition. In addition, the number of fixations was differentiated by target size in the control condition but not in AE, AO, and MI. These findings highlight the difference between random eye movements made in the control condition and task related eye movements made in AE, AO, and MI.

Conclusion

There is evidence of age-related changes to gaze during AE but, due to the predicted incomplete neural overlap, some of these changes are associated with processes that are not represented in MI and AO. In this regard, the lack of neural sharedness has a facilitative effect and permits the practice of movement under conditions that are not influenced by functional loss. Some age-related changes in gaze are preserved across conditions, for example the eye movements linked to movement planning. As these sub-optimal eye movements appear part of the shared neural representation, opportunity exists to alter their behaviour during simulated movement. For example, in sport psychology and clinical rehabilitation, augmented visual feedback has been used to correct suboptimal gaze strategies. Given the posited neural sharedness between AE, AO, and MI, correcting sub optimal gaze behaviour in AO and MI should lead to a more optimal gaze pattern in AE. Re-learning movement under these conditions, in absence of AE, reduces the risk of injury in this population. Regardless of age, healthy adults appear to perform more accurately, and prefer, simulation conditions that are supported by detailed visual information. This may be because the availability and processing of sensory information is more optimally matched to AE under these conditions.

5 Study 3: The influence of visual perspective on simulation procedures

5.1 Introduction

The influence of visual perspective on motor simulation remains unclear and is an area that has remained relatively unexplored (Morris et al., 2005). Humans perform actions physically in a 1PP. In simulated motor learning, actions can be observed and imagined from many perspectives and visual angles to address the needs of the individual or the performance outcome (see Chapter Two). A suggested benefit of simulating movement from an alternative perspective, such as 3PP, is that it supplements the visual information that is ordinarily available during AE (Hardy, 1997). In AO, this supplementary information may include information related to movement kinematics and information related to goal intention acquired from joint social gaze with the agent of the action. Studies presented earlier in this thesis have reported that younger and older individuals prefer performing, and perform more accurately, in AO (1PP) compared to MI (1PP), and it has been reasoned that this may be because the eye gaze representation in this covert process is most similar and, therefore, familiar, to AE. If this is true, it could be speculated that there would be little difference in the eye gaze representation between AO (3PP) and MI (3PP), given that actions are not physically performed in this perspective. In contrast, however, some have suggested that observation from a 3PP is as familiar as observation from a 1PP given the increased exposure to the actions of others across the lifespan (Vogt, Taylor, & Hopkins, 2003). Given that simulation procedures may involve actions presented in the 3PP, it would seem pertinent to understand the potential benefits (e.g., supplementary information) and drawbacks (e.g., reduced motor familiarity) of this perspective. The main aim in this study, therefore, was to examine the influence of perspective on simulation procedures.

During AO (3PP), observers tend to focus on the agent's gaze (if this information is available) and it has been suggested this behaviour is natural and automatic (Griffin & Bock, 2000; Letesson & Edwards, 2012). This gaze strategy is suggested to allow the observer to obtain early cues regarding the intention of the observed agent. The sensitivity of gaze to action intention is highlighted by studies demonstrating that when an agent's body movements are occluded, the nature of the action can still be inferred if the observer observes the agent's gaze direction (Castiello, 2003). When visual information relating to an agent's head or gaze is unavailable, as in the 1PP, observers fixate the stimulus end point in order to derive the specification of the movement (Mataric & Pomplum, 1998). In support of Mataric and Pomplum, earlier studies in this thesis have demonstrated that fixations to the stimulus end points occur during AO in a 1PP. Further, and in support of a shared motor representation, similar gaze behaviour is also executed in MI (1PP). To date, however, no research has comprehensively examined whether the eye movements executed during AO (3PP) are executed similarly during MI (3PP). If eye movements perform a functional role in MI (3PP) as they do in AO (3PP), then it is important to understand the degree to which the gaze is congruent. This was the focus of Part A of this chapter.

Investigating whether the eye movements executed during AO (1PP or 3PP) are represented similarly during MI (1PP or 3PP) is an important test of the Simulation Theory (Jeannerod, 2001). From an applied point of view, it is also important to understand how the eye movements executed during AO (3PP) are represented during MI (1PP) and, conversely, how the eye movements executed during AO (1PP) are represented during MI (3PP). For example, during motor rehabilitation individuals may be required to observe a therapist perform movement in the 3PP but simulate it (either through MI or through the early stages of AE) from the 1PP. Alternatively, in the sport domain, rock climbers may wish to inspect their form using MI (3PP) based predominately on visual information acquired in a 1PP. While it is generally accepted that humans can rotate objects mentally and, to a large extent, individual body parts such as the hands (Ionta, Perruchoud, Draganski, & Blanke, 2012; Sirigu & Duhamel, 2001), the cognitive processes associated with the rotation of a more complex action has not been examined fully. Given the increasing use of AO and MI as motor learning techniques it would seem pertinent to address this shortfall in the literature. Part B of this chapter addressed this issue.

Part A: The influence of perspective on gaze congruency during simulation

In Chapter Two, numerous studies demonstrating similar gaze behaviour durig AO (1PP) and MI (1PP) were discussed. These findings suggest it may be intuitive to expect that the eye movements in AO (3PP) would be similarly represented during MI (3PP), and that the eye movements would include those related to the pursuit of early action understanding. Indeed, some of the theories discussed earlier (section 2.2.2), such as Kosslyn’s Visual Buffer Hypothesis (Kosslyn, 1987) and Thomas’ Perceptual Activity Theory (Thomas, 1999) would support this idea. Other researchers (Johanasson et al., 2010), however, posit that eye movements may be performed in VI to relieve the working memory load; eye movements do not have to be executed but are likely to be executed when the task is complex. In this explanation, it may be reasonable, therefore, to expect eye movements (fixations) to be directed to critical aspects of the imagined scene/action (e.g., areas involved with hand-object interaction) rather than the model's gaze. Elucidating the functional role of eye movements during MI is further complicated by the inherent differences between perception and mental imagery. Pylyshyn (2003) argued that scene perception is primarily a 'bottom up' process and that the acquired information is interpreted dynamically, whereas VI is a primarily 'top down' process that involves the representation of information that has already been interpreted. This explanation suggests that the gaze behaviour may behave differently in the two processes: in perception the eye movements may be influenced by the information processing demands; for example when the information to be interpreted is complex, fixation duration would be longer. In VI, however, the eye movements would be influenced less by information processing demands as the information has already been interpreted and stored in memory. Evidence from Chapters Three and Four would add support to this contention. In these studies, fixation duration was influenced by task complexity (information processing demand), with increases in fixation duration accompanying increases in task demand. This effect was most apparent in AE and AO suggesting that information is interpreted differently in MI. These findings support the work of others (Hayhoe & Ballard, 2005; Williams et al., 2002) and suggest that for near aiming tasks individuals acquire and process visual information in AE and AO just at the point that is it is needed in a task.

The contrasting views on the functional role of eye movements during MI, coupled with the paucity of studies that have investigated the influence of perspective on eye movements during simulation reduces the formulation of an evidence-based hypothesis. To date, only one study has investigated the influence of perspective on eye movements during AO and MI (McCormick et al., 2012). McCormick et al. compared eye movements during MI and AO of a reach and place action presented in a 1PP and a 3PP. They reported both similarities and differences in the gaze metrics between perspectives and suggested that not all the visual information acquired in AO is presented in MI. Of particular interest to the current study was the finding that the number of fixations was differentiated by perspective in AO but not in MI. It is therefore possible that information relating to action intention and movement kinematics is acquired during AO but only the movement kinematics is represented in MI. If this is true, the eye movements in MI may not be a re-enactment of those executed during perception (Kosslyn, 1987), and the scene may not be inspected in a similar manner in MI and AO (Thomas, 1999). The purpose of Part A in the current study, therefore, was to extend the work of McCormick et al. and examine the extent to which information acquired during AO (1PP and 3PP) is represented in MI (1PP and 3PP).

Part B: Prime perspective congruency

During motor learning, AO frequently precedes AE or MI and is referred to as a ‘prime’. Priming involves presenting the performer with similar task-relevent visual information immediately before the task is performed. Priming is suggested to facilitate performance by activating and strengthening the shared mental representation (Brass, Bekkering, & Prinz, 2001; for a more thorough explanation see Hesse, de Grave, Franz, Brenner, & Smeets, 2008). Behavioural studies report that priming AE with AO reduces reaction time, and priming MI with AO improves MI ability (Rymal & Ste-Marie, 2009). Supporting the idea of a shared neural network, when AE is primed by AO (Brass et al., 2001), or MI (Ramsey, Cumming, Eastough,

& Edwards, 2010), faster reaction times have been recorded when the prime is congruent compared to incongruent. TMS studies have also demonstrated that when MI of simple hand movements is primed by AO, higher levels of motor excitablity are observed when the AO and MI involve congruent tasks (Fourkas et al., 2006; Vargas et al., 2004). Collectively, these studies suggest that an incongruent prime may activate dissimilar motor processes leading to an interference in the subsequent task.

The sensitivity of the performance outcome to the congruency of the prime is highlighted in studies that have demonstrated interference effects when subtle differences are present. Brass et al. (2001) reported that when the task was congruent but the direction of the movement incongruent (i.e., finger tapping with palm facing down or finger tapping with palm facing up) interference effects were also introduced. The influence of prime congruency may have implications for the traditional way in which AO is delivered. For example, if an individual is required to observe an action from an anatomical 3PP prior to performing it (AE or MI) in a 1PP, the difference in movement direction difference could introduce interference, resulting in a less than optimal motor learning outcome.

To date, interference effects have largely been examined using reaction time as the dependent variable (Brass et al., 2001; Ramsey et al., 2010). Reaction time may, however, not be the most accurate measure as some visuomotor tasks can be initiated without all of the visual information having been processed. For example, a grasping movement may be initiated with the orientation of the hand adjusted online (Hesse et al., 2008; Van Sonderen & Denier Van der Gon, 1991; also see the introductory chapter, section 2.4, eye movements). A more accurate and dynamic measure may be eye gaze registration. In earlier chapters, it has been demonstrated that certain fixation parameters, for example the number of fixations and fixation duration, are linked to information processing demands and are highly influenced by task complexity. The measurement of these parameters in priming studies may reveal the effect of prior information of subsequent movement planning. The aim of Part B of this study was, therefore, to use gaze metrics to examine the influence of the prime perspective when MI is primed by AO.

With respect to Part A of this study, it was hypothesised that similar eye movements to stimulus end points would be executed in MI and AO in both a 1PP and 3PP. Given the lack of previous empirical studies, no formal hypothesis was made regarding the eye movements relating to social gaze. With respect to Part B, it was hypothesised that the eye movements in MI would be influenced by the congruency of the prime perspective.

5.2 Methods

Nineteen participants were initially recruited for the study. Not all individuals perform voluntary eye movements during MI (Brown, 1968; Heremans et al., 2008), it was therefore important to test for this ability. Previous studies have reported that when task related eye movements are performed during MI (1PP), the eye movements mimic closely those of AE. Heremans et al. (2008) demonstrated that during the MI (1PP, unassisted by visual cues) and AE of a cyclic horizontal wrist movement between two targets, fixations are executed to both targets in a cyclic manner during both processes. Participants' recorded eye movements were therefore inspected to ensure they attended the movement-related targets (Cup Pick Up, Cup Placement) in during MI (1PP) a cyclic manner. The gaze strategy of eleven participants was identified as being unsuitable and this data was discarded. The remaining participants (N = 8, 43.25 yrs ± 5.42, five females) had normal or corrected to normal vision and were assessed as being right handed (mean laterality index: 92.26 ± 10.94; Oldfield, 1971). All participants were naïve to the hypotheses being tested and provided written consent to take part. The protocol were approved by a Departmental Ethics Committee at the Manchester Metropolitan University and conducted in accordance with the Declaration of Helsinki.

Measures

MI ability characteristics were assessed using the Vividness and Movement Imagery Questionnaire -2 (VMIQ-2; Roberts et al., 2008) and the MIQ-RS (Gregg et al., 2007; see section 3.2 for a description). This VMIQ-2 questionnaire comprises 36 items separated into 3 categories: 12 items for VI in a 1PP; 12 for VI in a 3PP; and, 12 related to kinaesthetic imagery. The completion of this questionnaire requires participants to imagine a variety of tasks such as kicking a football or throwing a stone and to rate their vividness of the movement using a 5-point scale where 1 = a perfectly clear image and 5 = no image at all. In each category possible scores range from 12 (extremely good ability) to 70 (extremely poor ability). The MIQ-RS has been discussed in detail in section 3.2, page 58. All participants were assessed as having at least average imagery ability: global scores for the MIQ-RS = 75.89 ± 14.64), global scores for the VMIQ-2 = 89.47 ± 20.57.

Eye movements were recorded using an ASL Mobile Eye system (Bedford, Massachusetts). The average fixation duration in scene viewing is reported to be approximately 330ms (Henderson, 2003), however, a fixation is usually defined by a lower threshold in the sports literature, typically > 100 ms (Vickers, 2007). In accordance with others who have examined cognitive performance during scene viewing (Liman & Zangemeister, 2012), a threshold slightly greater than that adopted in sports literature was selected. A fixation was defined as stable gaze within 0.8° visual angle for > 200 ms.

Task and stimulus

The stimuli in the experiment consisted of two 25 s video sequences of a repetitive grasp and place movement performed by a model, presented in a 1PP and a 3PP (see Figure 5.1). Specifically, the movement involved a model (male, 27 years) reaching forward with his right hand to pick up a cup that was position 16 cm in front of his body, aligned with his left side. The cup was subsequently set down on a saucer positioned 16.81 cm away to the right. The movement was completed with the model returning his arm to the right side of his body, with palm faced downwards and resting on the table. The movement took 5 s to complete and was repeated 5 times in each video sequence. The videos were presented on a 32" LCD screen (Logik, L32DIGB20) positioned at a distance of 87 cm from the seated participant. The participants placed their hands around the base of the chin rest to ensure they were in a neutral position (i.e. in a position that was incongruent to both MI (1PP) and MI (3PP). The experiment took place in a black booth to reduce visual noise. Participants' eye movements were recorded during AO and MI in four target conditions: (i) MI (1PP) preceded by AO in a congruent perspective; (ii) MI (1PP) preceded by AO in an incongruent perspective; (iii) MI (3PP) preceded by AO in a congruent perspective; and (iv) MI (3PP) preceded by AO in an incongruent perspective. Conditions were randomised and counterbalanced.

Prior to AO, participants were instructed to ‘observe with the intent to imagine the action in the same (or rotated) perspective at later time’. Subsequently, participants viewed the video and performed MI when instructed. The MI instructions prompted participants to use both kinaesthetic and VI (these processes had been explained prior to familiarisation) and to imagine the action five times. Participants were allocated 25 s to complete their MI (the same amount of time as AO) and during this time the LCD screen remained blank. The instructions and visual stimuli were presented using DMDX software (Forster & Forster, 2003).

Participants performed 80 trials: 2 (simulation: AO and MI) x 5 (number of trials in each simulation) x 2 (perspective: 1PP and 3PP) x 2 (congruency) x 2 (number of repeated blocks) during a total recording session of approximately 30 minutes. Each block of trials was separated by a 60 s rest. Following each rest period the calibration of the eye tracker was checked.

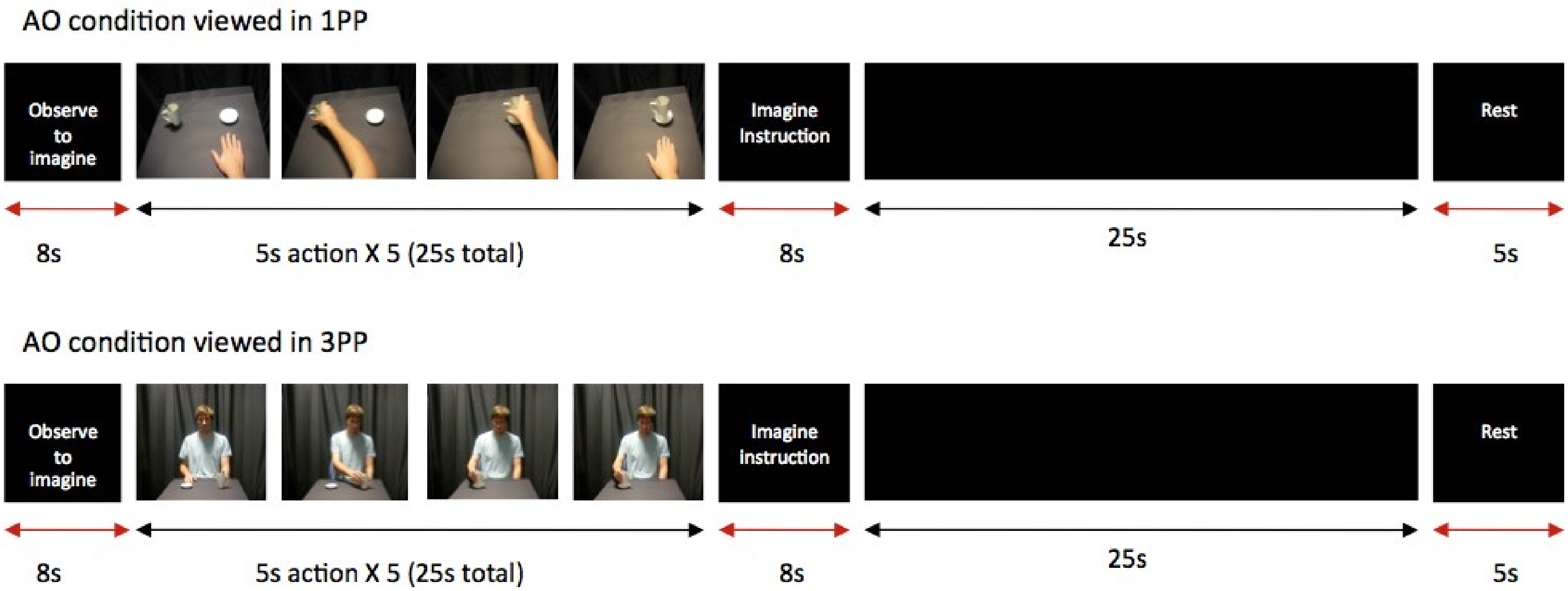


Figure 5-1: Schematic overview of the experimental protocol.

Data analysis

As social gaze has not yet been examined during MI it was difficult to predict accurately the gaze strategy during MI (3PP). Individuals have been reported to rotate, change the size or shape, reorganise or reinterpret their images during VI (Finke, 1989). In the absence of evidence suggesting otherwise, it is possible that some of these manipulations also occur during MI (3PP). An *a posteriori* approach to defining the ROIs was therefore adopted. In this approach ROIs are determined based on the regions most heavily fixated during the task. The method, also known as intelligent regionalisation, is suggested to be a valid for investigating cognitive processes linked to AO and MI (Liman & Zangemeister, 2012). The total scene viewing area = 480 (height) x 640 (width) pixels, where 1 pixel (px) = 1.4 mm. Note: Where applicable the data are reported in pixels as this unit of measurement is suggested to be appropriate when the stimulus is shown on a computer screen (Holmqvist et al., 2011). The ROIs included: the position of the cup at pick up (Cup Pick Up: 75 x 185 px); the position of the cup at placement (Cup Placement: 75 x 185 px); and an anchor position (Anchor: 75 x 225 px; see Figures 5.2 and 5.3). The area outside of the task related ROIs but within the total scene viewing area was classified as the Outside ROI. The Anchor ROI was defined as the area surrounding the resting hand/lower arm in the 1PP (Figure 5.2), and an area of equivalent size surrounding the head/upper body in the 3PP (Figure 5.3). Using a similar approach as others (Laeng & Teodorescu, 2002), the ROIs were generously sized and allowed for individual differences in compression and expansion of the mental image. This ensured that a standard method of quantifying gaze could be applied across participants and conditions, irrespective of any idiosyncratic behaviour. For both

Part A and Part B, the number of fixations within the ROIs was computed and used to infer attention. The average fixation duration was also computed and used as a measure of information processing. With respect to Part A of the study, a vector analysis was performed to examine how social gaze was represented during MI. To achieve this, the group mean fixation location in each ROI was plotted for AO and MI, 1PP and 3PP. Subsequently, the distance between the mean fixation location in the Cup Placement ROI and the Anchor ROI (in AO and MI) was computed. The angle (β) between the Cup Pick Up, Cup Placement ROI and Anchor ROI, was also calculated using the Law of Cosines: $b^2 = a^2 + c^2 - 2 \cdot a \cdot c \cdot \cos(\beta)$ (Figure 5.6b). Paired-sample t-tests were used to examine the differences in the inter-fixation distance and angle between AO (1PP) and MI (1PP), and AO (3PP) and MI (3PP).

Statistical analysis

Values for skewedness and kurtosis were used to identify normal distribution (Kim, 2013). Sphericity was assumed if Mauchly's test of sphericity was > 0.05. Effect sizes were calculated using partial eta squared values (η_p^2) and the alpha level for significance was set at $p < 0.05$. Pairwise comparisons were Bonferroni corrected. All data are presented as mean ± standard error.

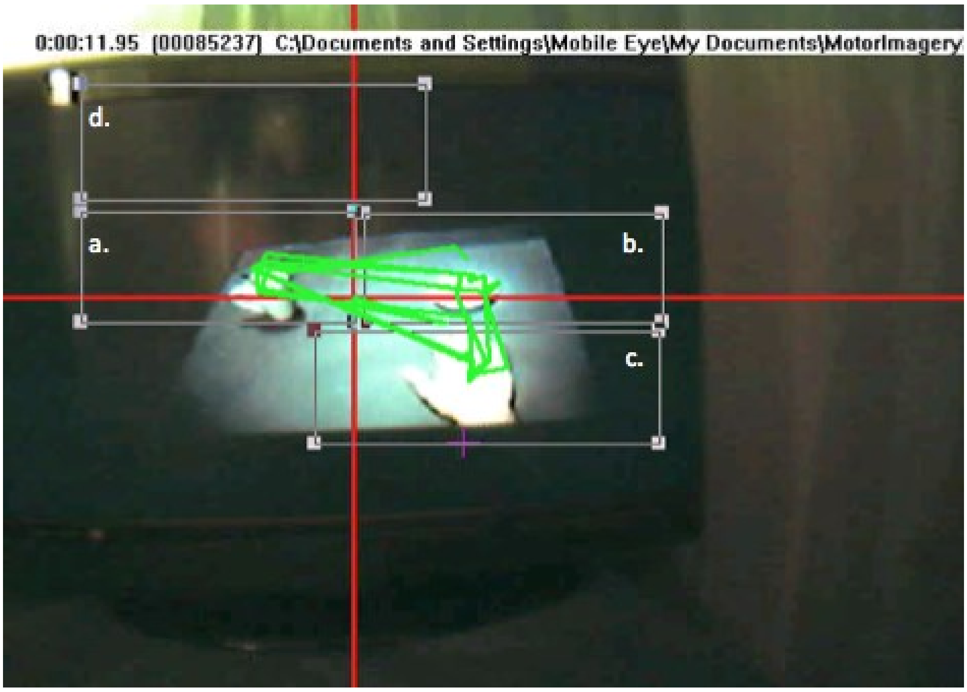


Figure 5-2: ROIs defined in the 1PP.

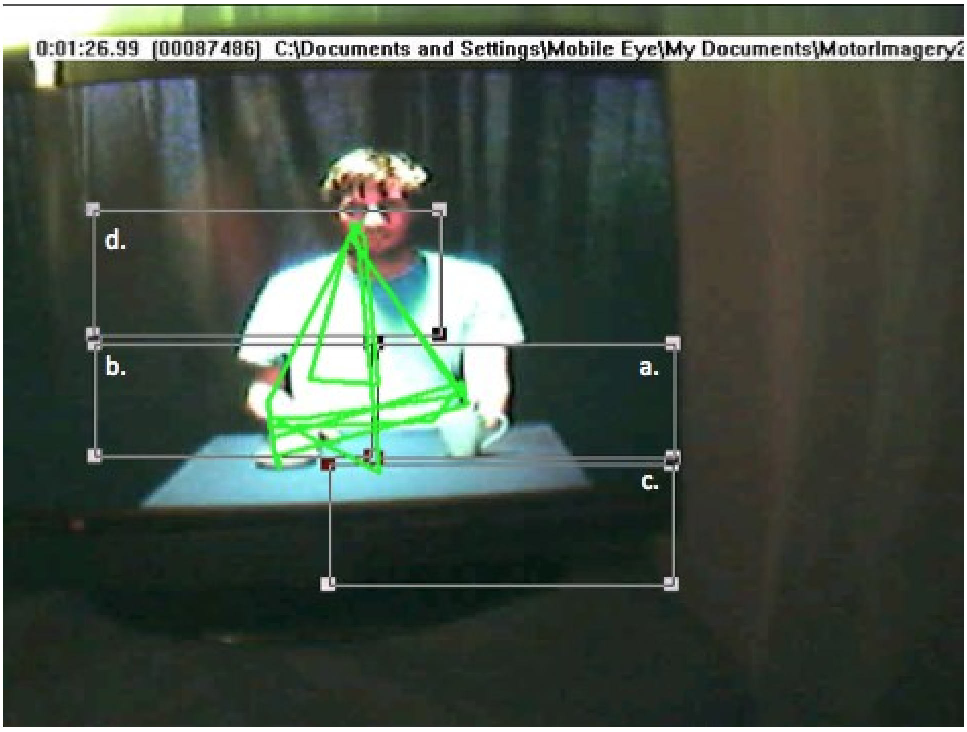


Figure 5-3: ROIs in the 3PP. For Figure 5.2 and 5.3: (a) Cup Pick Up; (b) Cup Placement; (c) Hand/Arm ROI; (d) Head/Torso.

5.3 Results

Part A

To address Part A of the study, the number of fixations and average fixation duration were compared separately using 2 (simulation type: AO, MI) x 2 (perspective: 1PP, 3PP) x 4 (ROI: Cup Pick Up, Cup Placement, Anchor, Outside) RM ANOVAs.

Number of fixations

There were significant main effects for: simulation type ($F_{1,7} = 18.343$, $p = 0.004$, $\eta_p^2 = 0.724$), more fixations were made in AO (10 ± 0.189, $p = 0.004$) compared to MI (8 ± 0.552) and, ROI ($F_{3,21} = 54.278$, $p < 0.001$, $\eta_p^2 = 0.886$), more fixations were made to the Cup Placement ROI (13 ± 0, $p = 0.005$) compared to the Cup Pick Up ROI (10 ± 0). Significantly fewer fixations (3 ± 1, $p <0.001$) were also made to the Outside ROI compared to the task-related ROIs (Cup Pick Up ROI = 10 ± 0, Cup Placement ROI = 13 ± 0, Anchor ROI = 10 ± 1). The main effect of ROI was qualified by a significant simulation type x ROI interaction ($F_{3,21} = 27.448$, $p < 0.001$, $\eta_p^2 = 0.797$). Pairwise comparisons revealed a greater number of fixations to the Cup Placement ROI in AO (18 ± 1) compared to MI (9 ± 1). In addition, in AO only, there was a significant difference in the number of fixations to the Cup Pick Up ROI (10 ± 0) compared to the Cup Placement ROI (18 ± 1; see Figure 5.4). There was a main effect for perspective, which approached significance ($F_{1,7} = 5.011$, $p = 0.060$, $\eta_p^2 = 0.417$); more fixations executed in the 1PP (10 ± 0, $p = 0.060$) compared to the 3PP (8 ± 1).

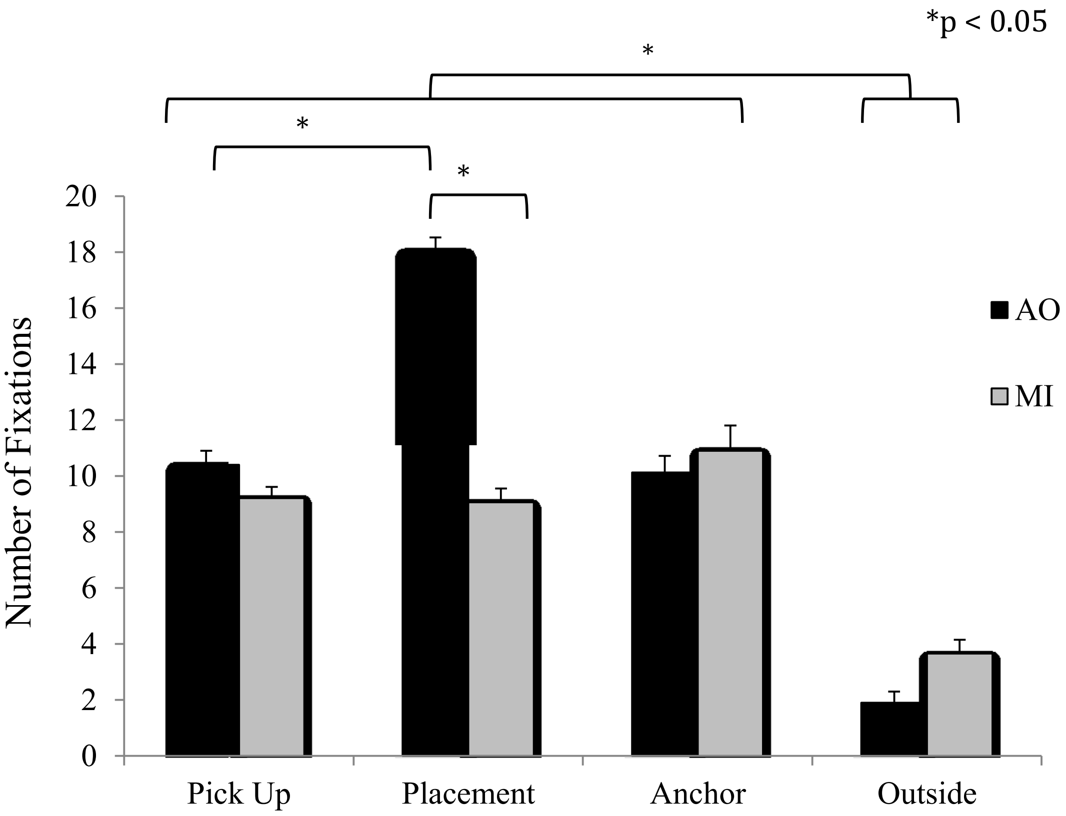


Figure 5-4: Number of fixations to the ROIs during AO and MI (perspective collapsed).

Average fixation duration

There was a main effect of ROI ($F_{3,21} = 21.456$, $p < 0.001$, $\eta_p^2 = 0.754$), which revealed that average fixation duration was significantly greater in the Cup Pick Up ROI (0.421 ± 0.019 s) compared to Anchor ROI (0.252 ± 0.029 s). The average fixation duration in the Outside ROI (0.252 ± 0.029 s, $p < 0.013$) was also significantly less compared to the task-related ROIs (Cup Pick Up ROI = 0.421 ± 0.019 s; Cup Placement ROI = 0.394 ± 0.014 s; Anchor ROI = 0.331 ± 0.018 s). The main effect of ROI was qualified by a significant ROI x simulation type interaction ($F_{3,21} = 5.238$, $p = 0.007$, $\eta_p^2 = 0.428$). Pairwise comparisons revealed that the average fixation duration in AO was significantly greater to the Cup Pick Up ROI (0.482 ± 0.037 s, $p = 0.020$) and Cup Placement ROI (0.436 ± 0.029 s, $p = 0.038$) compared to MI (Cup Pick Up ROI = 0.359 ± 0.011 s, Cup Placement ROI = 0.352 ± 0.009 s) (see Figure 5.5). The pairwise comparisons also revealed that in AO the average fixation duration was significantly less to the Anchor ROI (0.338 ± 0.023 s, $p = 0.041$) compared to the Cup Pickup ROI (0.482 ± 0.037 s).

There was a main effect for perspective that approached significance ($F_{1,7} = 4.882$, $p = 0.063$, $\eta_p^2 = 0.411$). Average fixation duration was greater in the 1PP (0.368 ± 0.018 s) compared to 3PP (0.330 ± 0.017 s in the 3PP).

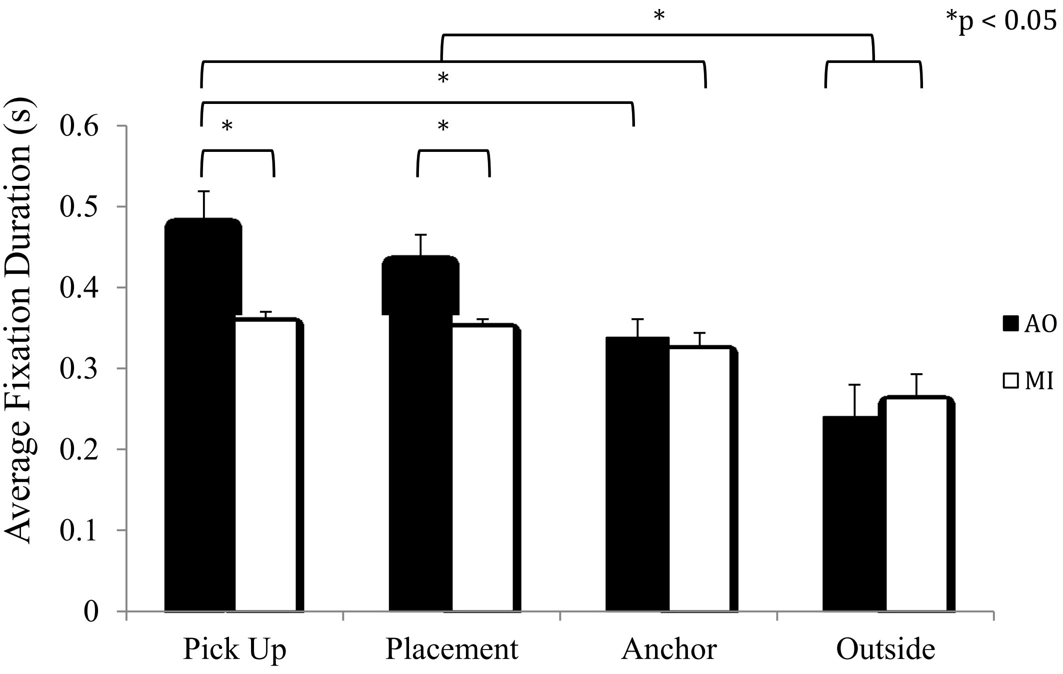


Figure 5-5: Average fixation duration in the ROIs during AO (perspective collapsed).

Vector analysis

In the 3PP, the distance between the Cup Placement ROI and the Anchor ROI was significantly greater during AO (137.180 ± 4.851 px, $p < 0.001$) compared to MI (49.666 ± 7.243 px); (t)7 = 12.666, $p < 0.001$. There was also a significant difference in the angle *abd* in AO (70.000 ± 1.96°) and MI (29.111 ± 8.16°); (t)7 = 5.994, $p = 0.001$. In the 1PP, the distance between the Cup Placement ROI and the Anchor ROI was significantly shorter in AO (44.628 ± 2.038 px) compared to MI (74.262 ± 13.863 px); (t)7 = -2.433, $p = 0.045$. There was a significant difference in the angle *abc* in AO (97.886 ± 6.321) compared to MI (70.018 ± 4.528); (t)7 = 3.398, $p = 0.011$; see Figure 5.6).

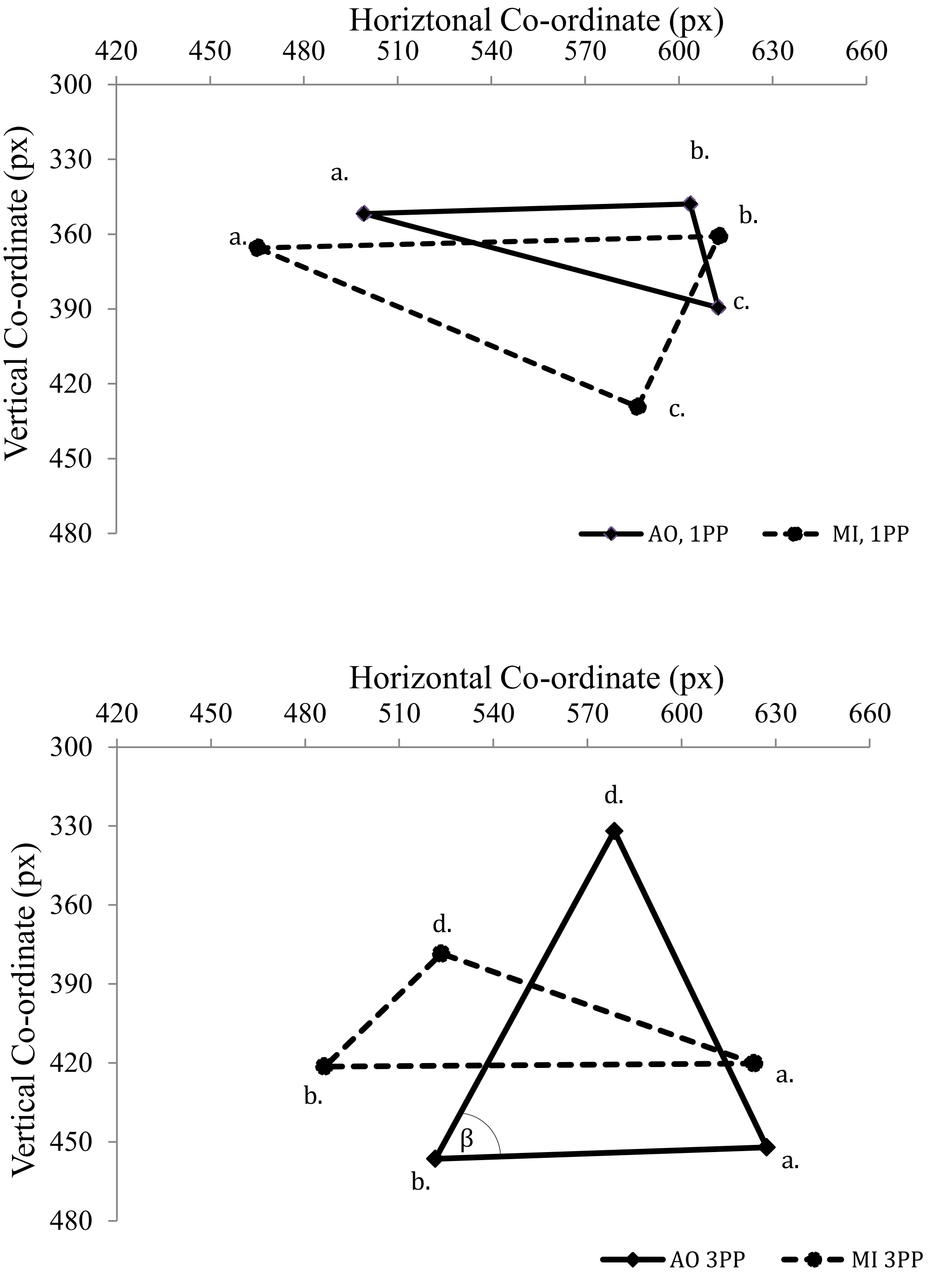


Figure 5-6 (a and b): Group mean fixation location during AO and MI in the 1PP (Figure 5.6a) and in the 3PP (Figure 5.6b). Cup Pick up ROI (a), Cup Placement ROI (b), and Anchor ROI (c and d). β is the angle *abc* and *abd* (illustrated only on Figure 5.6b for clarity).

Part B

To examine the effects of prime perspective, the number of fixations and average fixation duration in MI were compared using two separate 2 (perspective: 1PP, 3PP) x 2 (congruency: congruent, incongruent) x 5 (ROI: Cup Pick Up, Cup Placement, Correct Anchor, Incorrect Anchor, Outside) RM ANOVAs. In this analysis both of the Anchor ROIs were included to examine if an incongruent prime perspective resulted in fixations to the incongruent Anchor position during MI. For example, during MI (1PP) the Correct Anchor ROI would be the Hand/Arm ROI and the Incorrect Anchor would be the Head/Torso ROI. In contrast, during MI (3PP), the Correct Anchor would be the Head/Torso ROI and the Incorrect Anchor would be the Arm/Hand ROI. Significant differences in gaze metrics between the two MI conditions (congruent and incongruent AO prime) would suggest that the AO perspective does influence subsequent MI. Main effects and interactions for congruency are reported.

Number of fixations

There was a main effect of ROI ($F_{4,28} = 34.622$, $p < 0.001$, $\eta_p^2 = 0.832$), which revealed that significantly fewer fixations were executed in the Outside ROI (4 ± 1, $p = 0.006$) compared to the task-related ROIs (Cup Pick up = 10 ± 1, Cup Placement = 10 ± 1, Correct Anchor = 10 ± 0, Incorrect Anchor = 0 ± 0). In addition, significantly fewer fixations (0 ± 0, $p = 0.011$) were made to the Incorrect Anchor ROI compared to all of the other ROIs. There was a significant perspective x congruency interaction ($F_{1,7} = 8.388$, $p = 0.023$, $\eta_p^2 = 0.545$). Pairwise comparisons indicated that when MI (3PP) was preceded by an incongruent prime (i.e., the action presented from the 1PP), the number of fixations (ROIs collapsed) was significantly greater (7 ± 0 fixations) compared to when MI was preceded by a congruent prime (5 ± 1 fixations) (see Figure 5.7). The perspective x congruency x ROI interaction also approached significance, $F_{4,28} = 2.619$, $p = 0.056$, $\eta_p^2 = 0.272$. Pairwise comparisons revealed that when MI (3PP) was preceded by an incongruent prime, a significantly greater number of fixations were made to the cup pick up ROI (12 ± 2, $p = 0.051$), compared to when the prime was congruent (8 ± 1).

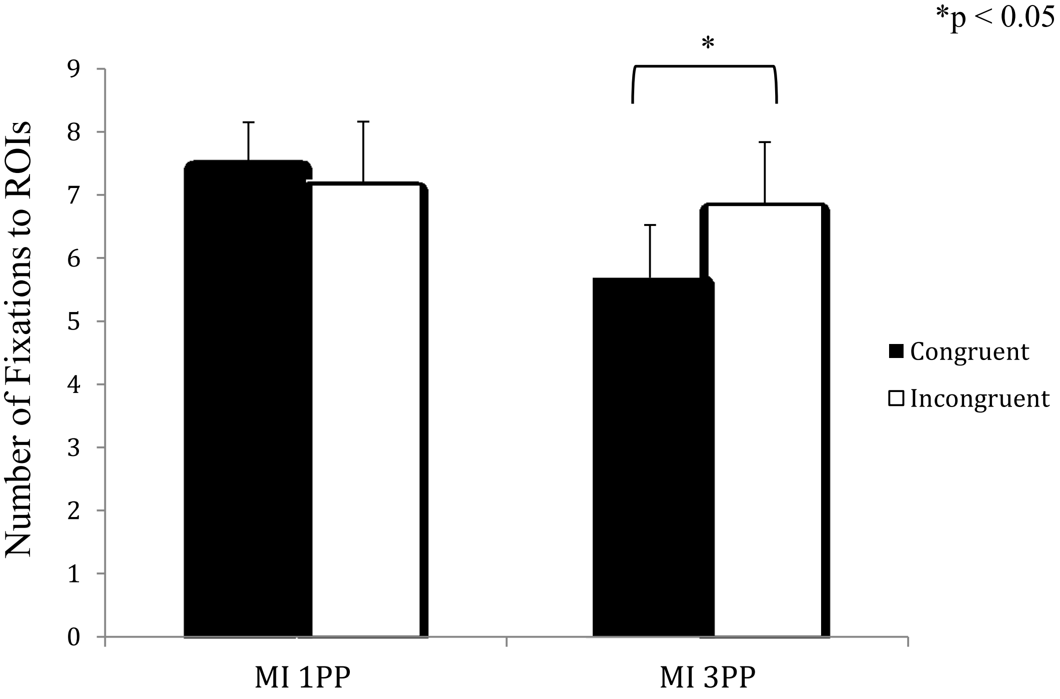


Figure 5-7: Number of fixations to the combined ROIs during MI preceded by a prime in a congruent and incongruent perspective.

Average fixation duration

There were no main effects or interactions for congruency. The average fixation duration was 0.268 ± 0.015 s in the congruent MI condition and 0.245 ± 0.017 s in the incongruent MI condition.

Data validation

As the ROIs were generously sized, the intra-individual precision of the fixations within the ROIs was assessed using a RM ANOVA. The 2 (simulation type: AO, MI) x 3 (ROI: Cup Pick Up, Cup Placement, Anchor) x 2 (location: x co-ordinate, y co-ordinate) RM ANOVA revealed a significant main effect for simulation type ($F_{1,7} = 29.284$, $p = 0.001$ $\eta_p^2 = 0.807$). The location of the fixations was less precise in MI (13.205 ± 0.632 px) compared to AO (7.956 ± 0.656 px). Given that there is variability in the data when full visual cues are provided, an increase in variability when visual cues are omitted was not surprising. An additional analysis was performed to assess the relative spatial accuracy of the eye movements in AO and MI. This was achieved by comparing the ratio of the inter-fixation distance between Cup Pick Up and Cup Placement, and between Cup Placement and Anchor. A non-significant difference between the ratios was deemed as evidence of spatial accuracy. The paired sample t-tests revealed no significant difference in the ratios for AO (2.488 ± 0.176) and MI (2.291 ± 0.363); $t(7) = 0.513$, $p = 0.624$.

The data from the AO (1PP) and MI (1PP) congruent conditions were used in the analysis as there is only guiding literature for gaze behaviour in the 1PP (Heremans et al., 2008) but not the 3PP. These validation tests suggest that using generously sized ROIs did not compromise the integrity of the data used to analyse the experimental conditions.

5.4 Discussion

This study investigated the influence of perspective, in particular social gaze, during the AO and MI of a simple reach-hand-place task (Part A). In addition, the influence of prime perspective was examined in conditions where MI was preceded by an AO prime, presented in either a congruent or incongruent perspective (Part B).

Part A

Part A of this study sought to examine how visual information acquired during AO (3PP) is presented during MI (3PP) and how this may differ compared to a 1PP. Participants observed a video of a reach-grasp-place action presented from a 1PP and a 3PP and performed MI from the same perspective immediately afterwards. The similarity in gaze behaviour was assessed by comparing fixation parameters in task relevant ROIs.

Number of fixations

In both perspectives, the ROIs attended to in MI were similar to those inspected during AO and included the Cup Pick Up, the Cup Placement and the Anchor ROI. The increase in the number of fixations to the Cup Placement ROI in AO suggests this was an information rich area. As the eye movements in AO and AE are suggested to use the same motor plans (Flanagan & Johansson, 2003), the additional fixations to the Cup Placement ROI in AO may reflect a similar visual search strategy to AE. In support of this suggestion, Williams et al. (2002) reported that in near aiming tasks skilled individuals fixate only one or two stimuli from a range of task related visual cues and that this represents a more economical gaze strategy. During AO, the visual information in this ROI may have been acquired to assist in the accurate placement of the cup onto the saucer during the 'homing' in phase of the movement (see Chapter Two, section 2.2). In MI, however, this particular ROI did not receive significantly more fixations than any other ROI (in 1PP or 3PP). This suggests that the gaze strategy was not as economical in MI, or that the information was simply being represented in MI but interpreted in AO (Ballard, Hayhoe, & Pelz, 1995; Pylyshyn, 2003). If, as Johansson et al. (2010) argue, fixations are executed to relieve working memory, then the similar number of fixations to each ROI during MI would add support to the view that the subcomponents of the task are not differentiated by complexity during MI, and were simply being represented. It must be remembered, however, that the number of fixations only represents one aspect of the gaze strategy. To substantiate these claims, the average fixation time must also be considered (see *Fixation duration* section, this chapter).

More fixations were executed in the 1PP compared to the 3PP, in both AO and MI. This finding suggests a different strategy was used in each perspective and, in support of a common motor representation, that the different strategies executed during AO were maintained during MI. These findings support, in part, those of McCormick et al. (2012) who reported that the number of fixations increased in the 1PP compared to the 3PP for AO only. The contrasting findings for MI may be due to the different methods used to assess the eye movements. McCormick et al.

determined the ROIs a priori, based on the exact location of the visual stimuli during AO. In the current study, the ROIs were determined a posteriori and allowed for expansion, compression, and spatial repositioning of the image. This latter approach is suggested to be more appropriate than the a priori approach for investigating top-down guided gaze strategies (Johansson, Holsanova, & Holmqvist, 2005; Liman & Zangemeister, 2012).

The increase in the number of fixations in the 1PP (in AO and MI) may indicate that this perspective was more complex. Some (e.g., Lorey et al., 2009) have suggested that the 1PP, in contrast to the 3PP, provides a more ‘embodied’ experience during MI, although this may be influenced by the agent of the action and the body position adopted (Stevens, 2005). It is possible that the 1PP (AO and MI) generated a greater degree of kinaesthesis compared to 3PP. This may have influenced the simulated kinematics of the action and increased task complexity. In accordance with Johansson et al. (2010), the increase in task complexity would have resulted in additional fixations to alleviate working memory load.

The Cup Pick Up and Cup Placement were common ROIs in 1PP and 3PP, albeit 180° out of phase. The Anchor ROIs were, however, not common; in 1PP the Anchor ROI included the Hand/Arm resting position, and in the 3PP it included the Head/Torso position. In each perspective, fixations were made to the appropriate Anchor ROIs in AO and MI. As the Anchor ROI in the 3PP included the head and torso, it is possible that the eyes fixated different body parts during AO and MI. For example, they may have fixated on the model’s gaze during AO, but fixated elsewhere on the torso during MI. Therefore, the specific location of gaze with the

Anchor ROIs was computed and compared between simulation conditions (see *Vector analysis* section, this chapter).

Average fixation duration

The average fixation duration was longer in AO compared to MI suggesting a reduced information processing demand in MI. This finding contrasts with the VI literature which reports that fixation duration increases in VI and memorisation tasks compared to perception (Jeannerod, Jouvet, & Jovet, 1962). The reduced fixation duration in MI could indicate that not all of the information processed in AO was represented (or required) during MI (Finke, 1989). Alternatively, the reduced fixation duration in MI could support Pylyshyn’s (2003) argument that the information had already been interpreted prior to MI. There were no differences in the average fixation duration between the Cup Pick Up and Cup Placement ROIs. Given that additional fixations were made to the Cup Placement ROI in AO, this finding further supports the earlier interpretation that the Cup Placement ROI was deemed the most informative cue. These findings suggest that in AO, but not MI, the information is processed dynamically at the specific time it is needed in the task. The tight coupling of eye movements to task evolution has been described by others (Hayhoe & Ballard, 2005; Williams et al., 2002), and this ‘just-in-time’ approach to information acquisition may be responsible for the increased processing demand in AO. The apparent temporal uncoupling of the movement in MI may have implications if the action to be imagined has a strict gaze-effector co-ordination pattern such as in gait. In AO, fixation duration was significantly less in the Anchor ROI than in the Cup Pick Up ROI. This suggests that information processing demand was not high for this region in either perspective, and indicates that the participants obtained the majority of their information from the stimulus end points (Mataric & Pomplum, 1998). In MI, however, the participants fixated the Anchor ROI in a similar manner to the other ROIs. This finding further supports the view that the sub-components of the task in MI are being represented and not interpreted (Pylyshyn, 2003), and that the visual search strategy may not be as economical as in AO (Williams et al., 2002).

There was a difference in the average fixation duration between the 1PP and the 3PP which approached significance ($p = 0.063$). Similar to the discussion for number of fixations, it could be speculated that the increase in fixation duration reflected a more embodied experience in the 1PP (Lorey et al. 2009). As force is suggested to inform MT (duration) and is coded in the motor representation (Decety, et al. 1989), fixation duration may represent a gaze metric that is linked to movement kinaesthesis. Indeed, in the sport domain it has been suggested that the duration of the final fixation prior to movement onset in a basketball free throw reflects the cognitive processes involved in planning the direction, force and velocity of the upcoming movement (Vickers, 1996). More contemporary research has also demonstrated that in certain goal directed tasks (e.g., the golf putt) the QE duration extends beyond movement onset and supports the online control of the movement (Vine et al., 2013). It is possible that a similar phenomenon could occur during simulation with dynamic visual representation (whether perceived or imagined) linked to regulating the control of movement. Given that the literature surrounding the kinaesthetic imagery modality remains unclear, this particular fixation parameter may be a useful marker to inform the Simulation Theory debate.

Vector analysis

One of the aims of this study was to determine if, and how, social gaze is represented during MI. The results of the vector analysis suggest that the model's head and eyes are used to anchor the action during AO (3PP). During MI (3PP) the action is anchored further down the torso towards the model's arm and hand. This suggests that the eye movements executed during MI (3PP) do not reflect social gaze and are related to the movement kinematics. Further, the findings suggest that in MI (3PP), as in MI (1PP), the action is spatially-coupled to the perceived action. It may be intuitive to suggest that if the action is re-anchored to the effector during MI (3PP), the process could involve kinaesthetic elements. In his early work, however, Jeannerod suggested that the imagination of the self, or other, in action from a 3PP is primarily a visual process and does not elicit any kinaesthesis (Jeannerod, 1994). A surprising finding was that the mean anchor position in the 1PP was also different between AO and MI. During MI, the mean fixation location in the Anchor ROI moved closer to the participant's mid-line. This may suggest that the participants were using their own effector as the action's anchor position. If this finding is considered in parallel with the earlier findings (that the number of fixations and average fixation duration is increased in the 1PP), it could be argued that the 1PP is a more embodied perspective. This may be because the information acquired through this perspective was more similar to the stored motor representation of the participant (Vogt et al., 2003), or because the participant's body position was more aligned with the information presented in the 1PP (Ambrosini et al., 2012; Brady, Maguinness, & Choisdealbha, 2011).

Part B:

Part B of this study examined the influence of prime perspective in conditions where MI was preceded by an AO prime. Participants observed a reach-grasp-place action presented in a 1PP and a 3PP and subsequently imagined the action in either a congruent perspective or in an incongruent perspective (i.e., a perspective that was rotated by 180°). The main focus of this part of the study was to understand how the eye movements executed during AO (3PP) were represented during MI (1PP) and, conversely, how the eye movements executed during AO (1PP) were represented during MI (3PP).

Number of fixations

The use of two independent Anchor ROIs in this experiment confirmed that MI was performed in the 1PP and the 3PP. The Anchor ROI in the 1PP, which included the hand and arm, was offset to the Anchor ROI in the 3PP, which included the head and torso. Fixations to the appropriate ROI, in either perspective, therefore provided a measure of participant compliance in the task. There were no fixations to incorrect Anchor ROIs during the tasks in either the congruent or incongruent prime conditions. This suggests that participants complied with the task and were able to mentally rotate a complex action. Further evidence of task compliance is that the number of fixations outside all of the ROIs was not significantly different between the congruent and incongruent conditions.

There was an increase in the number of fixations to the ROIs when MI (3PP) was preceded by AO (1PP). Further analysis revealed that these fixations were made to the Cup Pick Up ROI. In accordance with Johansson's view (Johansson et al., 2010) that eye movements during MI are linked to task complexity, this finding could suggest preceding MI (3PP) with an incongruent prime increases task complexity. The finding also supports previous work that has demonstrated an interference effect when movement type is congruent but movement direction is incongruent (Brass et al., 2001). In the current study, the movement direction was left to right in the 1PP, but right to left in the 3PP. The interference effect was not demonstrated when MI (1PP) was preceded by AO (3PP). This may suggest that the motoric coding of an action in the 1PP is relatively robust to interference. In support of this suggestion, a recent TMS study has suggested that congruent and incongruent motor simulation processes are managed simultaneously and appear to be temporally overlapped (Sartori, Betti, Perrone, & Castiello, 2014). Sartori et al. required participants to observe a soccer penalty kick in their direction, while simultaneously planning a complementary response action (i.e., parrying the ball). Sartori et al.'s findings suggested that the participants could simultaneously observe in the 3PP and imagine (plan) in the 1PP. It remains to be tested whether it is possible to observe in the 1PP and imagine (plan) in the 3PP.

Average fixation duration

There were no main effects or interactions for average fixation duration. This suggests that the information processing demands during MI were not influenced by the congruency of the prime perspective. In Part A of the study, it was reported that average fixation duration was not influenced by task complexity during MI. This finding could suggest that the visual information during MI is simply a representation of an action that had already been interpreted during AO. If this is true, it might be logical to expect a difference in the average fixation duration during the incongruent MI trials as the visual information acquired during AO is incongruent to the imagined action. The lack of any difference in the average fixation duration may suggest that the reach and grasp action used in this study, although complex compared to majority of studies in this area, was not sufficiently demanding or unique. As the action is likely to be observed repeatedly on a daily basis from a 1PP and the 3PP, its generation during MI may be a highly automatic task. Future studies should explore the use of a more demanding task.

From an applied point of view, these findings indicate that there is little interference when an everyday action is observed from a 3PP and subsequently imagined from a 1PP. This suggests that if AO is used during motor rehabilitation, simple actions may be presented in a 1PP or a 3PP without compromising the quality of the learning outcome. In contrast, however, the task demand in MI appears to be increased when it is performed in a 3PP but primed in a 1PP. These findings relate to a relatively simple, everyday task, the increase in task demand may be much greater for individuals who wish to use the MI (3PP) to improve form in highly skilled and complex movements.

General summary

In AO and MI (1PP and 3PP), task related eye movements are performed which may improve the cognitive economy of the task. In both perspectives the eye movements appear linked spatially and temporally to the evolution of the task in AO, but only linked spatially to the task in MI. In AO, information rich visual cues are fixated as a priority (e.g., the Cup Placement; Williams et al., 2002), and in MI, the fixations may reduce working memory load (Johansson et al., 2010) and improve visual recall ability (Brown, 1968). The eye movements executed in the pursuit of social gaze in the 3PP were not represented similarly during MI. In this regard, the findings do not fully support the theory that the eye movements in MI re-enact those of perception (Kosslyn, 1987), or the Perceptual Activity Theory that the scene is inspected in MI in a similar way to perception (Thomas, 1999).

A limitation with the current study concerns the size of the visual stimuli. Hesse et al. (2008) reported that the size of the prime stimuli influenced a subsequent grasp task, with individuals opening their hands wider in the smaller sized prime condition. Therefore, in order to maintain experimental control, the prime videos were filmed so that the cup and saucer were the same size in both perspectives. Although this resulted in the size of the upper limb in the 1PP being slightly larger than that in the 3PP, the size of the hand-object interaction remained constant.

The findings from these studies and those of previous chapters are now considered in the context of a prototype rehabilitation aid, the AST toolkit. The AST prototype was conceived as a best practice model, informed by the published research discussed previously and the eye gaze studies of this thesis. User groups were envisaged as coming from across general motor dysfunction populations but with a focus on older stroke groups. The following chapter describes the AST toolkit prototype development and proposes future directions for integrating the findings from this and previous chapters into support for motor (re)learning populations.

6 Action simulation therapy as a rehabilitation aid: The development of a tool for patients with motor impairments

6.1 Introduction

Movement dysfunction in elderly individuals is common and exacerbated further as part of debilitating illnesses, many with severe disability including upper limb dysfunction. In extreme cases, such as stroke, many patients (41-45%) experience chronic motor impairments and limitations in activities of daily living (ADLs; Wade & Hewer, 1987) even after extensive neurological rehabilitation. Many individuals also live their lives in socially-isolated disengagement which can further debilitate the cognitive impairment that comes with conditions such as stroke (Holmes & Ewan, 2007). Patients often require long-term dependence at a considerable cost to primary carers and to the National Health Service (NHS). It is, therefore, important to optimise cognitive and motor support following illness. AO of upper-limb movements, linked to physical and occupational therapy interventions, can facilitate rehabilitation compared to physical therapy alone (Ertelt et al., 2007). Building on the findings of the previous studies reported in this thesis, the aim of this study was to develop a novel toolkit with therapeutic benefits using a mental practice-type approach for individuals with motor weakness and motor dysfunction. This chapter reports the design of the App-based Action Simulation Training (AST) toolkit to support movement dysfunction. The design has, as its central premise, Simulation Theory (Jeannerod, 2001) and eye movement metrics.

A wealth of neuroscience research reported in this thesis indicates an interrelation between common sensory and motor processes, specifically regarding

AE, AO and MI. The potential relevance of these findings for improving methods in movement rehabilitation has been highlighted (c.f. Holmes, Cumming, & Edwards, 2010). During AO, visual and motor cortical areas, typically involved during AE, become activated. This neural activity subserves simulation of the observed action by the observer (Jeannerod, 2001) and primes motor execution (Heyes, 2001). A large number of brain imaging studies have now demonstrated that AO engages other motor regions of the brain and can facilitate basic motor parameters such as force production as well as more complex imitation learning (for a meta-analysis see Caspers et al., 2010). These findings suggest that action simulation procedures may offer new ways of stimulating motor weakness, regeneration and plasticity when motor function has been compromised by age, stroke or neurodegenerative disease. In support of this concept, a recent Cochrane database systemic review concluded that mental practice in combination with other treatment was more beneficial that the other treatment alone for treating post-stroke upper limb dysfunction (Barclay-Goddard, Stevenson, Thalman, & Poluha, 2011).

Simulation procedures currently in use for clinical purposes can be subdivided into studies involving AO, MI, and mirror box procedures. In the first clinical trial involving AO, Ertelt et al. (2007) recruited 8 participants with moderate post-stroke hemiparesis who attended 18 AO training sessions (each 90 min long) over a 3-week period. In each session the patients were asked to watch three 6-min video sequences showing hand and arm actions of daily life of increasing complexity, each followed by imitative motor execution with the impaired upper limb using the same object as used in the video. Significant functional improvement was found for the AO group compared to a carefully matched control group and the improvement was maintained 8 weeks post-training. fMRI during an independent object manipulation task identified significantly increased activations in the regions of the frontal primary motor cortex for the AO group, indicating markers of cortical plasticity stimulated by AO. Franceschini et al., (2010) used a similar AO and AE intervention in a larger trial involving three centres for neurorehabilitation and also found positive effects for their sample of chronic stroke patients.

Evidence for the efficacy of MI in clinical rehabilitation has also been reported in three random controlled trials (RCTs). A small RCT by Liu and colleagues (2004) examined the effect of combined AE and MI, and found higher levels of independence on trained and untrained ADLs in the mental practice group. They failed, however, to find enhanced recovery on the standard Fugl-Meyer Motor Assessment (Fugl-Meyer, Jääskö, Leyman, Olsson, & Steglind, 1974). A second small RCT conducted by Page and colleagues (2007) found improved upper limb function after combined physiotherapy and MI training in chronic stroke patients. A third carefully controlled clinical trial (Ietswaart et al., 2011) did not find MI to be effective when delivered separate from AE in patients early post-stroke. This latter careful evaluation demonstrated that the key to mental practice efficacy may be found in the complex interplay between AE and MI (and AO). In support of this idea, Nedelko, Hassa, Hamzei, Schoenfeld, and Dettmers (2012) reported an increased neural activation when AO is combined with MI (compared to AO alone) and suggested that the higher order processes involved in MI, and the lower-order processes involved in AO complement each other when AO and MI are combined. The idea of combining AO and MI, which has roots in Jeannerod's early integrative account of AO and MI (Jeannerod, 1994, 2001), is supported by others (e.g., Holmes & Collins, 2001; Vogt et al., 2013)

The third cluster of studies involves mirror box procedures (see review by Ramachandran & Altschuler, 2009) where individuals watch movements of their dysfunctional limb via a mirror in the spatial location of that limb. In two controlled trials, the 'mirror therapy' was found to improve the neurological status of post-stroke patients immediately after the intervention as well as in a follow-up trial (Dohle et al., 2009; Michielsen et al., 2001). Mirror box therapy is similar to AO, involving prescribed AE and sensory afferents from the limb contralateral to the putatively observed limb. The difference, however, is that the patient is instructed to move the functional limb in order to replicate activity that would be observed in the paretic limb. In contrast, in AO, participants are typically still throughout the AO experience.

This discussion provides evidence for the efficacy for combined AE, AO, and MI procedures in clinical rehabilitation. The appeal of mental practice as a potentially low-cost and effective neurorehabilitation technique for movement weakness and dysfunction, however, belies the difficulty of delivering these mental practice techniques (Holmes, 2007). Earlier chapters in this thesis have highlighted the sensitivity of mental practice techniques to delivery factors (see Wakefield et al., 2013). In healthy individuals and under laboratory conditions, these delivery factors include the type of action that is simulated; the adoption of an allocentric, egocentric, specular or anatomical view; the agent of the movement; task compliance; task ability; task instructions; and priming. In the clinical domain, there are additional delivery factors related to the individual (for a review see Holmes, 2007) and to the management of the resources that need to be considered. Holmes and Ewan (2007) reported some of these issues in their development of a structured AO aid for stroke rehabilitation. They provided patients with a large liquid crystal display screen to watch videos of meaningful movements and demonstrated positive change in psychological affect and physical activity levels. They reported that post-stroke individuals preferred simulation procedures from a 3PP and suggested that this may due to a decrease in the individual's functional motor activity and an increase in the AO of others. The development of the concept tool, whilst effective for a case study, was logistically and financially unsuitable for wider delivery across hospital and community environments for a large number of patients. Further, Holmes and Ewan did not consider eye movements in their study design. These constraints highlight an important, and often over looked, reciprocal relationship that challenges the development and application of research in this, and other, domains; the ability to transfer training interventions effectively and efficiently from the 'bench to the bedside', or from the laboratory to the field (Harle & Vickers, 2001; Williams & Grant, 1999), and back again.

6.2 Delivering action simulation procedures

By drawing on recent technological advances from other domains, researchers are able to address some of the challenges associated with delivering action simulation procedures. In the sports domain, Harle and Vickers (2001) were some of the first researchers to report that a pre-shot and computer-based cognitive intervention influenced the gaze strategy of university basketball players and precipitated a positive change in the mechanics of a far aiming task. The participants improved their free throw accuracy by more than 22 %, and the intervention led to a more economical visuomotor routine (a more stable and extended QE duration and a faster shot MT). More recently, Put et al. (2013) demonstrated a web-based approach to training the cognitive-perceptual skills of referees. Specifically, referees were asked to observe on-side and off-side passes during 'staged' football match scenarios in an attempt to improve the accuracy of their offside decision making skills. The videos were filmed from an aerial viewpoint and that of the assistant referee (i.e., 3PP on the side line). The cognitive-perceptual skills of the referees were found to improve following the AO training and, importantly, the improvements transferred to a real-world setting. These findings suggest that multi-user AO interventions can train specific skills if tailored and delivered in an appropriate manner. In the clinical domain the use of interactive computer applications for training purposes has also been reported to improve motor function and participant engagement (Badia & Cameirao, 2012; Reinthal et al., 2012). Reinthal et al. (2012) used a within-subject pre to post-test paradigm that involved post-stroke individuals performing prescribed movements whilst observing themselves as an avatar in a video game. The authors reported motor improvement, as assessed by the Fugl-Meyer Motor Assessment (Fugl-Meyer, 1974), following the intervention. The authors commented that the level of self-initiated, goal directed practice was greater than that typically performed by individuals during traditional outpatient therapy. Motor (re)learning through a simulated environment (virtual reality) has also been suggested to be more superior to that achieved through AE because the tasks are less dangerous, more fun, and easier to learn due to the additional salient feedback that can be provided (for a review see Holden, 2005). Training via virtual reality allows the user to experience a simulation of a real world by using hardware devices to monitor movement kinematics and provide simulations of haptic and force feedback to the user. This advantage can, however, be the biggest drawback; the peripheral equipment is often complicated and expensive and this may hinder the widespread adoption by health care centres and the general public. The AST toolkit considers the advantages and drawbacks of these emerging technologies to deliver a movement practice tool that is scientifically-rigorous, low-cost, portable, and widely accessible. The novel idea of combining covert processes such as AO and MI, as well as AE, offers prolonged opportunity to consolidate particular motor processes in a safe environment. This may be of particular importance in older groups where individuals may fatigue more quickly during traditional physical movement therapy sessions.

User centred design

Embedding motor rehabilitation inventions in interactive systems is still in its infancy. An individual's motivation has been established as a fundamental process in motor learning (Bandura, 1962; Maclean, Pound, Wolfe, & Rudd, 2000), however, there appear few systems that have put the user at the heart of the design process. User centred design (UCD) is defined as "a philosophy based on the needs and interests of the user, with an emphasis on making products usable and understandable" (Norman, 2002; p.188). It is a process in which the needs of the users dominate the design of the interface, and the needs of the interface dominate the design of the rest of the system. Systems that are highly usable are considered to: (i) increase productivity; (ii) reduce human error; (iii) reduce training and support; and (iv), improve user acceptance and trust (Maguire, 2001). Cameirao, Badia, Oller, and Verschure (2010) developed the virtual reality based Rehabilitation Gaming System which used rehabilitative principles and psychometric evaluation to provide personalised and automated AE training for post-stroke patients. To assess usability the authors asked the patients (N = 9) four questions regarding their experience of using the tool. The majority of respondents reported they that enjoyed the task and found the task was easy. Such a limited, discrete and disjointed assessment of usability may, however, lead to poor usability in the longer term (Gulliksen et al., 2003). A key principle of USD is that representative users participate early and continuously throughout the system's life cycle and that the development of the system involves an iterative process cycling between design ideas, prototyping and evaluation (Goransson, Gulliksen, & Boivie, 2003). When such an approach is adopted, the long-term engagement with the system, defined as the degree of voluntary use of a system along a wide period of time (Febretti & Garzotto, 2009), may be improved. Engagement and motivation have been identified as key factors associated with stroke (Tupper & Henley, 1987). Demotivated individuals are reported to invest less effort into rehabilitation programmes, resulting in slower progress (Holmes & Ewan, 2007). When progress is slow, individuals become increasingly frustrated and may disengage from their rehabilitation programme (Maclean, et al., 2000). As identified by others (Badia & Cameirao, 2012), the benefits of a simplistic motor rehabilitation interactive system is that is widely accessible, uncomplicated, and can be used in unsupervised setting. In terms of engagement, however, these features may also represent its greatest challenges; there is little motivational support and the limited sensitivity of performance measures may not always detect progress. In addition to usability, the 'playability' of an interactive system is also reported to influence long-term engagement. In the clinical domain, the motor function of patients is often different to that of healthy populations and highly personalised training plans, adjusted to the capability ('playability') of the patients, are required (Holmes, 2007). For example, research has suggested that altering the speed of an action during mental practice can facilitate motor (re)learning (Heremans et al., 2012a; Louis et al., 2008). The default speed of the action may need to be set to match the capability of a user with specific motor dysfunction. Engaging interactive systems need to acquire behavioural information about the patient's motor capabilities so that the speed of actions can be matched appropriately, and adjusted periodically, to suit the individual's rehabilitation needs. The evidence reviewed in this section suggests that if effective, uncomplicated, and widely accessible motor rehabilitation interventions are to be developed, then the system's usability and playability should be considered. These ideas are now evident within the United Kingdom's NHS where individualised, stratified, patient centred medicine is promoted.

Delivery factors

Designing effective practice interventions for individuals in the clinical domain is complex. In the introductory chapter, two comprehensive sets of guidelines relating to the delivery of MI (see Figure 2.1) and AO (see Figure 2.2) were identified. The guidelines for some delivery factors may be generalised to the clinical domain (e.g., tasks that are represented in the hMNS appear to respond well to mental practice in healthy and clinical populations), however, some factors such as optimum training duration remain unresolved. Schuster et al. (2011) concluded that in healthy individuals an average of 4 x 17 minute sessions of MI a week for 3 weeks (194 minutes) typically showed positive results. In outpatient therapy, however, the recommended duration is longer, with 12-16 x 36 minute sessions (432-576 minutes) typically required for significant motor improvement (Reinthal et al., 2012). Determining the optimum training duration by corroborating results from clinical populations can also be difficult. In a clinical study involving chronic stroke patients (> 1098 days post stroke), Ertelt et al. (2007) reported performance gains following 18 sessions of combined AO and AE, (total AO therapy time = 810 minutes). In contrast, Ietswaart et al. (2011) reported no performance gains in patients (< 180 days post stroke) following involving 12 x 45 minute sessions and 8 x 30 minute session (total minutes = 780) of MI. In both studies, the mental practice time was similar but this did not lead to similar outcomes. The contrasting findings may have been due to a number of delivery factors such as the type of practice (AO), perspective, task complexity, and clinical factors such as the extent of functional or cognitive deficit, support systems, or number of days post-stroke, that were not controlled similarly in each study. These findings highlight the difficulty faced by researchers and practitioners in designing effective simulation procedures in the clinical domain. Indeed, a recent skills audit (Wilson, Smith, Stockley, & Holmes, 2012) revealed that clinicians (physiotherapists and occupational therapists) used MI and AO asystematically during therapy and that they had little knowledge about how to design an effective intervention. This lack of expertise may be a consequence of the limited recommendations that are available through the National Clinical Guidelines for Stroke: “People with stroke should be taught and encouraged to use mental practice of an activity to improve arm function, as an adjunct to conventional therapy.” (Intercollegiate Stroke Working Party, 2012, p. 92). The availability of a standardised training package, or toolkit, which is underpinned by neuroscientific and clinical research, may assist researchers and practitioners in designing and implementing effective simulation training packages.

The influence of gaze

The findings from the studies presented earlier in this thesis suggest there are additional delivery factors that need to be considered during simulation procedures. In Chapters Three and Four it was demonstrated that the use of visual cues, and in particular dynamic visual cues, significantly improve the congruency of the cognitive processes between mental and physical performance. These findings suggest that AO may be a more effective technique for actions that require temporal control. If MI is used for such actions, then dynamic cues should be included to enhance the temporal congruency with AE. The findings from Study 2 also revealed some age-related changes in the gaze strategy. There was evidence that primary fixation following the go signal significantly undershot the target in AE, AO and MI. This finding suggests that older individuals execute a less than optimal gaze strategy in both overt and covert motor performance. The location of the final fixation prior to movement onset is reported to be one of the trainable parameters of the QE (Vickers, 1996). Researchers have demonstrated that cognitive interventions can be used to optimise this gaze parameter and improve motor performance in athletic and clinical populations (Crowdy et al., 2002; Harle & Vickers, 2001). Of potential importance to individuals with cognitive decline is that in sport these strategies are reported to simplify the skill and lead to an economy in thought (Harle & Vickers, 2001). Often cognitive interventions involve verbal task instructions to illustrate the task goal (Crowdy et al., 2002), or require some physical practice (Harle & Vickers, 2001). For some clinical patients, these approaches may not always be appropriate; verbal instructions may increase cognitive load and physical practice may be temporarily impossible or present a safety risk. An alternative method of orienting visual attention is through the use of exogenous visual cues (Hagemann et al., 2006). Hagemann et al. demonstrated that in a healthy, young population transparent red patches overlaid onto informative cues during AO can be used to orient attention and improve motor performance. This may be a particularly useful method for orienting attention in the older, clinical population as it is suggested to permit attention to be focussed without increasing cognitive load (Moore, Vine, Cooke, Ring, & Wilson, 2012). The findings from the penultimate study of this thesis, Study 3, revealed that in MI (3PP), a model's face and head were not attended to. In AO (3PP), however, they were inspected as a priority in an attempt to understand the goal intention of the model (Castiello, 2003; Letesson & Edwards, 2012). This may present a possible area for interference if psycho-sociological factors such as ethnicity, age and gender are not congruent between observer and observed. In support of this suggestion, increases in specific physiological responses (skin conductance; Sattler, 1970), and decreases in memory recognition (Zhao & Bülthoff, 2013) are reported to occur when other-race co-specifics, compared to similar-race co-specifics, are observed performing similar functions. It may, therefore, be prudent for motor cognition toolkits to control the model's demographics if simulation-based neural benefits are not to be compromised. The findings from Study 3 also revealed some differences in fixation parameters (number of fixations, fixation duration) between 1PP and 3PP, which may be related to kinaesthesis. The data therefore support the inclusion of actions presented from a combination of perspectives to provide a more holistic motor learning experience.

In summary, these findings suggest the importance of highlighting the spatial and temporal aspects of the task relevant cues along with clear instructions as to the goal and intention of the task. These important factors were a priority for the development of the AST toolkit and derive directly from the eye movement studies reported in this thesis.

The aim of this project was to design a structured AST toolkit based on current neuroscience, clinical research, and the findings of earlier eye movement studies in this thesis. The objective was to create a tool, based on a user-centre design, that could improve intra and inter clinic/laboratory reliability by controlling delivery factors during simulation procedures. The toolkit aimed to interface seamlessly between the laboratory and motor rehabilitation setting, thus facilitating the reciprocal 'bench to bedside' relationship and increasing ecological validity.

6.3 Method

This project was funded, in part, by a competitive university research award from the Knowledge Exchange and Innovation Fund. The project review committee, which included the Chair of the University Ethics Committee, approved the study.

The development of the AST toolkit was based on the principles of UCD, formalised in the ISO-standard 13407 (ISO, 1999). The UCD process involved a multi-disciplinary team including older (healthy and clinical) adults, physiotherapists, occupational therapists, psychologists, researchers and software designers. Consultations with representative users (e.g., healthy and clinical adults, and clinicians) took place across a number of regional stroke support groups (e.g., stroke support groups in Crewe, Nantwich and Mid-Wales) and NHS hospitals in the NW of England and Mid-Wales over a period of four months. This permitted data gathering from in-patient and community settings. Driven by a collaboration of evidence-based research, user requirements and software capability, the design process was highly iterative and cycled between proposals from the multi-disciplinary team, prototyping (paper and modelling), and evaluation (see Figure 6.1). A basic prototype AST toolkit was developed early in the design process to allow the concept of the tool to be discussed in a meaningful way and facilitate user data-driven decision making (Goransson et al., 2003). The functionality of the tool was determined through a mixed-methods approach that involved integrating data-driven user requirements within a theory-driven framework. These approaches are explained below.

Determination of user requirements

The aim of this pilot work was to identify the users' needs or requirements of post-stroke rehabilitation therapies from the patients' and clinicians' perspective. The philosophical framework adopted was a general inductive approach (Thomas, 2003), as a description of the users' needs was required. Semi-structured interviews were used based on a series of fixed questions with scope for users to expand on their responses. This type of interviewing is suggested to be useful in situations where broad issues are understood but the range of interviewee's responses to the issues may differ (Maguire, 2001). It was anticipated that the responses between patient and clinician would vary as professionals frequently evaluate recovery using defined quantitative bench marks whereas patients focus more on activities that bring meaning to their life pre-stroke (Doolittle, 1992).

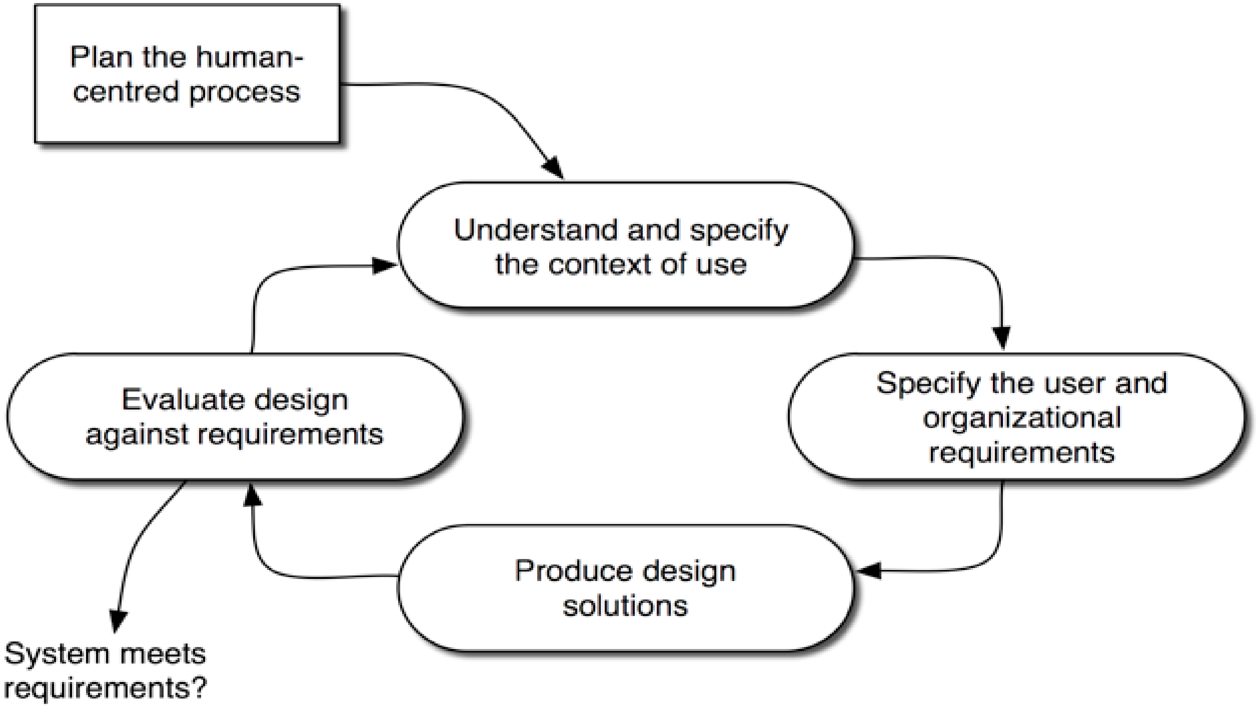


Figure 6-1: Key human-centred design activities from ISO-standard 13407 (ISO, 1999).

Individual and private discussions with, and observations of, 9 individuals affected by a first stroke (4 acute and 5 chronic) were conducted in a series of single sessions over four months. Twenty clinicians (physiotherapists and occupational therapists) were also consulted (10 in a focus group and seven individually in repeated sessions) during that time. The focus group was used to establish a collective view and to identify user requirements early in the design process (Nielsen, 2000). Those approached had either been admitted to (patients) or worked in (clinicians) the rehabilitation unit of a general hospital. Individuals were asked to describe their experiences of rehabilitation. In particular, they were asked to comment on the effectiveness, efficiency and user satisfaction of current techniques and the proposed AST toolkit. The approximate length of the interviews and focus group was 30 and 90 minutes, respectively. All individuals who volunteered to be part of this study were reassured about confidentiality in the reporting of the findings and agreed to the anonymous data being included for academic use.

Data analysis

The data were read in detail to obtain an understanding of the themes and events covered in the text. Text segments specifically relating to usability were highlighted and categories subsequently determined. To achieve a complete analysis, the categories were revised and refined until a framework incorporating no more than eight themes was achieved (Thomas, 2003). Informal member checks to establish the credibility of the findings were carried out with the clinicians and patients who were met on more than one occasion.

Findings

The analysis of the raw data yielded 8 first-order themes that were further thematised into four general themes: (i) independent learning; (ii) specificity of learning; (iii) competence; and (vi) engagement (see Figure 6.2). Some factors influencing usability are cited across higher order themes.

Independent learning

Both clinicians and users felt that current rehabiliation procedures were not efficient. Clinians felt they were limited to the amout of time they could devote to one-to-one therapy and were conscious of the lack of continuing rehabiliation in the community. Patients felt that most of their time in the rehabiliation centre was spent doing little to help their recovery. One patient's comments described this widespread issue:

"I'm just sat here, I've been here all day, I could be doing something. It's been like this for four weeks, I just move from one hospital to another but I don't seem to be making any progress"

Raw data themes	1st order themes	Higher order themes
unrestricted therapy [P]	autonomous	independent learning
intuitive, easy to navigate [CL, P]		
record of practice history [CL]		
lowtime cost to clinican [CL]		
lack of motor (re)learning in the community [CL, P]	proactive	
self directed rehabilitation [P]		
model's skin exposed in AO videos [CL]	specificity of learning	specificity of learning
correct position to perform movement [CL]		
patient led therapy [CL, P]		
accurate demonstration of home exercises via video [CL]		
complexity matched to motor ability of user [CL]		
correct position to perform movement [CL]	safety	competence
not doing further damage by exercising [P]		
family support during home exercise [P]		
perform beyond own expectations during therapy [CL]	achievement	
test myself, measure my own progress [P]		
fun tasks that progress in complexity [CL]		
complexity matched to motor ability of user [CL]		
constructive [P]		
frustrated at lack of progress [P]		
early acceptance of motor impairment [P]	amotivation	engagement
apathy towards rehabiliation (severe stroke) [CL]		
forgetfulness[CL, P]		
rural life - disconnected from clinical support team [CL]	accessibility	
low-cost [CL]		
easy to use [CL, P]		
encouragement from others [P]	social	
joint social gaze with model [P]		
alienated from pre-stroke life [P]		

Figure 6-2: Hierarchical inductive analysis of users’ needs influencing rehabilitation therapies. CL = clinicians' responses, P = patients' responses.

Specificity of learning

To improve the effectiveness of rehabiliation procedures, clinicans commented on the need for adjunct therapies to reflect clinical practice. They commented that the proposed AO videos should be filmed with the skin of the limb exposed and for the limb to be in a supported position. In addition, they commented that the tasks should meet the individual needs of the patient. The meaningfulness of the rehabiliation was highlighted by one patient's comment:

"my husband had a stroke a few years ago so I have to drive him around. I do all the driving, there is no one else, so I'll still have to do that….I have to get this [points to paretic limb] working".

Competence

Clinicans and patients indicated how important a sense of achievement was to user satisfaction during rehabilitation. A patient described how she had set her own achievement goals in the absence of any formal rehabiliation:

"I use to be a school teacher [before the stroke], so I knew I had a good vocabularly, much better than I have now. So I started to carry a thesaurus around and look up words. I'd test myself to see how many I could remember. It worked you know…slowly, but I did get better."

Engagement

Clinicians reported that the level of apathy towards self-directed rehabilitation in the clinical unit was high in some stroke individuals. Engagment with the rehabilitation programme was particularly problematic following discharge. Some patients readily accepted their motor impairment and did little home exercise, and other patients forgot how, and when, to do the exercises. Clinicans felt that an accessbile toolkit that contained AO videos and a training log would support personal rehabiliation in the community, particularly in rural areas:

> “once the patients living in rural areas leave hospital we rarely see them again at out-patients or at local stroke clubs. Many live on farms and have no access to public transport, they are isolated and their progress never gets followed up.”

The themes were integrated within the theory driven framework of Holmes and Calmels (2011) and are further discussed in the results section.

Theory driven framework

The Behavioural Modification Hypothesis predicted by the PETTLEP model has been demonstrated to apply similarly in MI and AO (Holmes, Collins, & Calmels, 2006), suggesting that both processes are influenced by similar delivery factors (Wakefield et al., 2013). As such, the comprehensive theory-driven guidelines for delivering AO (Holmes & Calmels, 2011) were adopted as simulation wide delivery factors in the AST toolkit. In addition, based on the findings of the studies presented earlier in this thesis, eye movements were also considered as a new delivery factor. A revised set of guidelines is shown in Figure 6.3.

6.4 Results and discussion

Researchers, clinicians, and patient users identified a need for adjunct rehabilitation methods to be low-cost, accessible, portable, inclusive and intuitive. The AST toolkit was developed in Xcode, the freeware integrated development environment designed for developing iOS Mac Apps (https://developer.apple.com). To increase accessibility, portability, and to permit ease of navigation of the tool through a touch screen interface, the iPad (trademark of Apple Inc.) was chosen as the initial device to deliver the rehabilitation therapy. Through appropriate selection on the user interface (see Figure 6.4(b)), structured AE, AO, and MI could be delivered discretely, or concurrently for enhanced cortical activity (Guillot, Moschberger, & Collet et al., 2013; Vogt et al., 2013).

Observation content

The AST toolkit was delimited to meaningful, upper limb actions known to be represented in the hMNS (e.g., grasp, grip, pinch and reach actions). The videos included audio information and were subdivided into three categories: (i) ADLs; (ii) action assessments; and (iii) specialised actions. The ADLs were subdivided into categories considered important in stroke rehabilitation (Nouri & Lincoln, 1987): domestic duties, personal care, communication, mobility and safety. Actions within these categories included, but were not limited to, washing up, counting money, putting toothpaste onto a toothbrush, making a call on a mobile phone, and reading a newspaper.

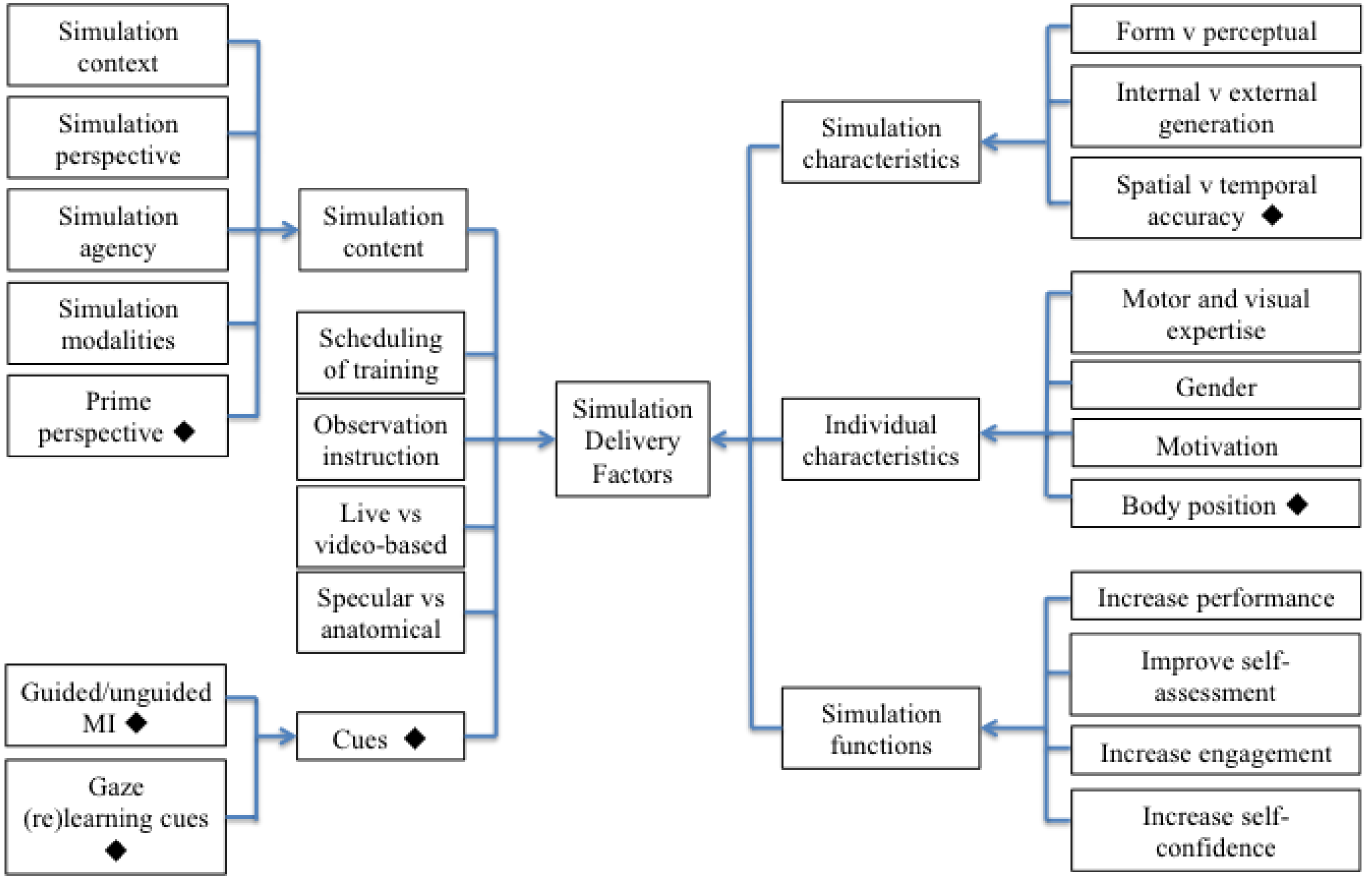


Figure 6-3: Revised delivery factors for the AST toolkit, based on the original delivery factors of Holmes & Calmels (2008). Diamonds indicate novel delivery factors determined through the eye gaze studies reported in this thesis.

The actions in the ‘action assessment’ category involved those typically performed during a patient’s in-hospital motor assessment. These actions were devised from a number of validated clinical motor assessment tools such as the Action Research Arm Test (ARAT; Lyle, 1981) and the Block and Box Test (BBT; Mathiowetz, Volland, Kashman, & Weber, 1985). In comparison to the ADLs, the actions in this category were less complex and typically involved simple movements such as pinching a pin, grasping a ball, and turning a screw. As the AE and MI performance of these tasks is measurable (e.g., time take to complete the task, number of tasks completed etc.), this action category permits ‘knowledge of results’ feedback to be given. This type of feedback is reported to accelerate learning and to be central to motor learning in a simulated environment (Holden, 2005). Future development of the AST toolkit could provide opportunities to measure the performance of the tasks in this category and for the clinician to ‘weight’ this feedback relative to the motor impairment of the individual. This action category was included following comments from clinicians that patients enjoyed the challenge associated with practising these tasks at the bedside. The category therefore addresses the usability needs for competence, engagement, and user satisfaction. To maintain consistency with rehabilitation techniques employed by therapists and address the usability needs for specificity of learning, the actions in this category were filmed with the skin of the upper limb exposed and the limb appropriately supported. In the 1PP, it was therefore possible for the user to adopt the same position as that of the model. Given that the model’s demographics could be matched to the user (see the observation agency section in this chapter), the AO provided an experience that was similar to self-observation and almost stratified therapy. The findings from Chapter Five and other research (Holmes & Collins, 2001; Stevens, 2005) suggest the congruency between the overt and covert performance would be enhanced under these conditions.

Future development of the AST toolkit could also provide a third category of upper limb movements called ‘personal rehabilitation’. This category could permit individualised actions to be uploaded by the user (or clinician) and incorporated within the training environment. These videos could be filmed during the physical and occupational rehabilitation sessions where, as reported by one of the clinicians, ‘patients perform beyond their expectation and are surprised and pleased with their achievement afterwards’. The inclusion of personalised exercises may increase motivation and serve as a reminder of the accurate way in which to perform exercises in the home environment. This third category addresses the user’s needs for competence and engagement.

Observation agency

To optimise the visual similarity between the user and the observed model, all actions stored in the video repository were filmed using a number of models of different ages, ethnicity and gender. A demographic selection algorithm based on these factors was used to select the most appropriate model to perform the actions, see Figure 6.4(a). This delivery factor limits any potential interference from psycho-sociological factors, addresses the PETTLEP model’s recommendations for behavioural matching during simulation procedures (Holmes & Collins, 2001), and meets the philosophy of Jeannerodian Simulation Theory.

Name
Gender: Male / Female
Dominant Hand: Left / Right
Skin Type: 1
Observe each video: 1 (1 -5 times)
Follow each video: 1 (1 -5 times)
Time between observation and action: 1 (seconds)
How many sets of each group: 1 (1 -5 times)

Adding salt to a pan: observe & action
Cutting with a knife: not used
Sprinkle sugar in tea: observe
Unscrew a jar lid: observe & action
Lifting a cup: observe & action
Using a water tap: observe & action
Stir a cup of tea: observe
Peeling an apple: not used (observe / observe & action / not used)

Figure 6-4: Screen shots illustrating the AST toolkit's user set up page (a), ADL task selection page (b), and hypothetical historical data (c).

Perspective

The findings of Study 3 suggested that different cognitive processes are involved in the 1PP and 3PP. In addition, the preferred perspective of the user (patient) may be influenced by their motor skill or task goal. Therefore, to provide a more holistic motor learning environment, actions from both perspectives were included in the toolkit. The videos in the 3PP were piloted with the model's gaze averted and not averted. The qualitative analysis indicated greater user satisfaction during the AO of videos in which the model's gaze was not averted, that is, when the user could engage visually with the model's gaze. The results from Chapter Five indicated that joint social gaze between user and model did not detract from the time spent processing critical haptic cues. Where possible, therefore, the gaze of the model in the 3PP videos was not averted. This delivery consideration addresses the usability needs for social engagement and the model's facial features and gaze should be seen as task-relevant cues.

Visual cues

Using a similar approach to others (Grant & Spivey, 2003; Hagemann, Strauss, & Canal-Bruland, 2006), the AST toolkit included exogenous visual cues to orient and retain attention. Transparent red patches were overlaid onto the videos (in AO) and still images (in MI) to provide a subtle increase in the perceptual salience of the information rich areas (see Figure 6.5).

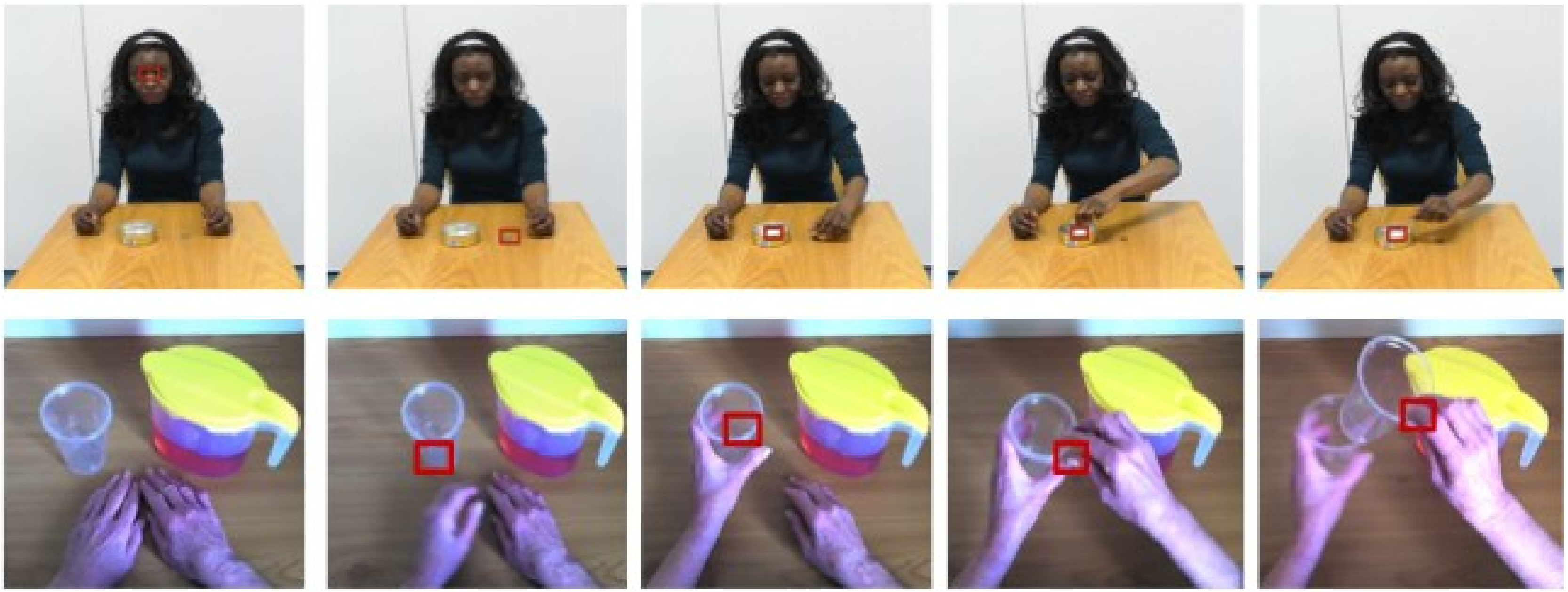


Figure 6-5: Transparent red patches used to exogenously orient visual attention during an ARAT-derived coin pick up task in the 3PP (top), and an ADL presented in the 1PP (bottom).

In cognitive interventions that involve the correction of ineffective gaze strategies, the desired gaze strategy is frequently based on those of experts (Harle & Vickers, 2001; Williams, Ward, & Chapman, 2003). In the AST toolkit, the placement of the red patches was therefore based on the eye movements (fixation location) executed by the younger, healthy individuals during the near aiming and reach-grasp-place actions in Studies 1, 2 and 3. Confirmation that these visual cues improved task performance can be drawn from the fact that when the visual cues were occluded (e.g., Study 1, UGMI condition), performance declined. It was anticipated that the use of saliency cues in this manner would help ensure that the task was attended to in the correct temporal and spatial manner, even if the pre-task instructions had been forgotten, ignored, or not fully understood (Underwood, Foulsham, & Humphrey, 2009). In addition to the exogenous visual cues, a progress bar was displayed at the top of the screen to indicate the temporal progression of the movement during MI. As older individuals are reported to be less effective at maintaining temporal congruency between MI and AE (see results from Study 2 of this thesis), the timing bar could be used to assist the temporal simulation of the movement. One potential drawback of using augmented feedback is that it could create a specific type of learning that may detrimentally affect performance when the feedback is removed (Hayes, Elliott, & Bennett, 2013; Nieuwboer, Rochester, Müncks, & Swinnen, 2009). Evidence from the sports and clinical domains, however, suggests that performance improvements acquired through AO based cognitive interventions are often retained many weeks after training (Ertelt et al., 2007; Harle & Vickers, 2001). It is possible that observing an action in the 3PP and imagining in a 1PP would limit the dependency on visual coding, although this hypothesis requires further testing.

The consideration of this delivery factor (visual cues) addresses the needs for competence and specificity of learning.

Scheduling of training

The AST toolkit is a voluntary adjunct to traditional physical therapy; it provides no set limits to practice time. The information pages include the recommendation that mental practice time should at least equal that of the physical practice time prescribed by the clinical team. Delivered in this unrestricted manner, the AST toolkit addresses the usability need for independent learning; the time spent in active recovery can be increased without an additional time cost to the clinicians. Therapists from two independent hospitals raised concerns regarding their own time-cost of implementing the AST toolkit. Other studies have also reported problems associated with therapist compliance due to logistical reasons (Bovend'Eerdt, Dawes, Sackley, Izadi, & Wade, 2010). To address these concerns, the AST toolkit has a simple graphical user interface with large, intuitive icons for easy selection and navigation. It has a moderate amount of error tolerance and contains self-help pages. The tool can be operated in ‘quick start’ mode using default parameters, or parameters can be user–defined when a more specialised approach is required. Targeted for clinical and at-home use, the AST toolkit can be operated without formal clinician input.

Future development of the AST toolkit involving cloud-based storage could provide clinicians with historical data relating to exercise adherence (see Figure 6.4(c)). This would ensure that the progress of all in- and outpatients in clinical care remains monitored.

Task instruction

Each task is prompted by explicit instructions. Prior to AO, the instruction is to ‘observe the following movement with the intention of performing the movement at a later time’. This specific type of goal-directed instruction has been suggested to activate a more optimal neural profile with greater similarity to that of AE (Iacoboni et al., 2005). The instructional set has, therefore, been used in many of the current motor cognition studies and shown to elicit stronger MEP responses during AO in TMS studies (e.g., Hardwick, McAllister, Holmes, & Edwards, 2012).

The instructions preceding MI included the generic Langian stimulus and response propositions, ‘imagine performing the movement you have just observed, recreate the image vividly in your mind and consider the physical sensations’. Although generic scripts are suggested not to facilitate the highest gains in performance (Williams, Cooley & Cumming, 2013), the scripts serve only as a prompt. Every MI task was preceded by AO, therefore the process was immediately primed (see Edwards et al., 2003) through contextually rich visual and audio information. The generic scripts prompt the visual and kinaesthetic recall of this recently acquired information.

Temporally-altered motion

Another important temporal aspect of simulation relates to the overall speed of the action. Study 2 of this thesis presented evidence that the physical and mental MT increases in healthy ageing. In post-stroke individuals MT is also reported to increase in AE, but it may increase or decrease in MI (Sirigu et al., 1996). Thus, a movement presented at a generic speed during AO may be incongruent with the typical action speed of the individual and this may influence the training outcome. Evidence from the MI literature suggests that the speed of MI influences subsequent motor performance. Specifically, speeding up a movement in MI has been demonstrated to subsequently decrease MT in AE in healthy young individuals (Louis et al., 2008). While this may be a wanted outcome in some interventions, in some situations the speed of a movement may need to be decreased so that critical aspects of the tasks, which may be overlooked in error in AE, are attended to AO and MI. As recommended by others (Nieuwboer et al., 2007), mental training techniques need to be appropriately matched to the motor ability of the individual. Determining the most appropriate speed to deliver the AO and MI training is a challenge, and one that is typically over-looked by practitioners. The AST toolkit addresses this issue by assessing the mobility of the user through a simple timed dexterity task performed during user set up. The task can be performed at comparable speeds by either hand, thus permitting a basic determination of motor ability regardless of hand dominance or paretic limb side. Once the task is completed, an algorithm computes the difference between the user's MT and the MT of the default AO action and adjusts the video speed accordingly. By periodically performing the timed physical task, the video speed can be adjusted to reflect any changes in performance. The user interface offers options to temporarily over-ride the user-defined speed to support the specific function of the simulation training (e.g., increase or decrease the task speed). This delivery factor addresses the usability needs for competence and specificity of learning.

The delivery and content of the actions was restricted to the performance of discrete or concurrent AE, AO, and MI. Contemporary research suggests that coordinative AO and MI, that is where the actions are different but can be coordinated with each other may offer additional benefits (for a review see Vogt et al., 2013). With respect to the clinical domain, it is possible that this type of practice scenario may be particularly beneficial for post-stroke individuals who experience difficultly in ordering the subcomponents of simple tasks, although this hypothesis remains to be tested. Another restriction of the AST toolkit was that all of the actions were presented in 2D. While this has some advantages, for example low-cost and reduced likelihood of experiencing cyber sickness (Holden, 2005), the approach may restrict depth perception. Future work will look to include the aerial perspective in the video repository as this perspective has been demonstrated to be effective in training cognitive perceptual skill (Put et al., 2013). The increasing availability of binocular eye gaze tracking systems will permit depth perception in AO and MI to be examined.

The presented study is the first step in the delivery of a low cost adjunct to motor rehabilitation. An aim for future studies will be to evaluate the usability of the AST toolkit and to examine its transfer to improve movement performance in an applied setting. In many ways the toolkit represents an integrated AO-MI version of the PETTLEP model and it would be interesting to see some of the PETTLEP studies repeated using a sport-based version of the AST. Williams and Grant (1999) suggested that valid training inventions should include: a competitive measure; a process measure; evidence of transfer into the real world; and a control group. These factors could be addressed in a clinical setting if the AST toolkit was tested in a pilot

RCT. With regards to the competitive measure, some of actions in the AST toolkit were devised from two clinical assessments of manual dexterity: the ARAT (Lyle, 1981); and the BBT (Mathiowetz et al., 1985). Measures of performance could therefore be assessed using either the ARAT or BBT. Process measures may include grip strength of the affected hand, reaction time, spasticity, or perception (eye movements). Regarding transferability, the toolkit was developed as an App and, as such, it can interface seamlessly between the laboratory and motor rehabilitation setting. Finally, a control group, which is a condition of the RCT, could involve a sample of patients receiving standard card and performing lower limb exercises (currently not included in the AST toolkit). The findings of such an RCT could be used to update the National Clinical Guidelines for Stroke (Intercollegiate Stroke Working Party (2008) and inform patient-centred clinical services.

Conclusion

In this project a novel toolkit with therapeutic benefits was developed for individuals with motor weakness and motor dysfunction. The functionality of the tool was based on a user-centred design, underpinned by neuroscientific research and best practice. The toolkit exploits the posited shared neural substrate between AE, AO, and MI, and maximises motor (re)learning by creating a highly useable and individualised training environment. By capitalising on accessible technology, the AST toolkit has potential to be deployed on a large scale and in remote areas. The USD ensures that the motor training tool is intuitive, engaging, and can be used to complement rehabilitation in hospital and after hospital discharge. In a similar manner to clinical evaluation, the toolkit can capture quantitative performance data thereby allowing the progress of an individual to be monitored over time.

7 Epilogue

This final chapter of the thesis aims to synthesise the findings from the programme of work. Throughout each study's discussion, the theoretical and applied implications, limitations and specific applications have been embedded and integrated into an on-going development of ideas leading up to the main practical application demonstrated within the AST toolkit. In this chapter, a concise summary of the main theoretical and applied implications of the thesis are presented and future research directions are discussed.

The programme of work was inspired by Jeannerod's (1994) seminal work in motor cognition in which he claimed that a shared motor representation could explain a common mechanism for AE and MI. Jeannerod also implied that the same mechanism could apply to AO. Within the neural equivalence arguments made in the paper, he provided evidence from both physiological systems and more central brain markers to justify the existence of a shared motor representation. There was, however, little reference to eye movements and certainly no detail as to the eye gaze metrics that might add to the list of 'functionally-equivalent' indices. Many researchers in motor learning attest that eye-gaze metrics can be seen as indirect markers of attentional processes, albeit primarily visual attention. The functional validity of both MI and AO processes as contributors to motor learning therefore rests heavily on the congruence of the eye metrics in the covert states with those measured in execution conditions when the task is performed successfully or when compared against the eye gaze metrics of a skilled performer. To date, this eye gaze congruence across a range of ecologically valid and theoretically-driven conditions (e.g., Fitts' Law; different visual perspectives; different age groups) has not been investigated empirically. Further, and importantly, the application for (re)learning eye gaze patterns associated with coordinated movement patterns and through an integrated AE-AO-MI approach is novel and paves the way for many alternative versions that are developed for specific groups (stroke, Parkinson's, chronic pain, sports performers etc.).

The first goal of the research programme was to examine a range of eye gaze metrics across the three simulation states in order to provide a valid and reliable technique to test Simulation Theory. Chapter Three reported the findings of a Fitts' Law task across the simulation conditions. The concept of a speed and accuracy trade-off being preserved in motor imagery had been proposed in 1989 by Decety et al. Here, the design was extended further by including not only an AO condition, but also by splitting the MI condition into guided and unguided conditions. Further, the objective eye movement markers were able to add greater granularity to the chronometry data that were published by Decety et al. and demonstrates the strength of triangulating methods. In the current study, there were differences between conditions for strategy and differences between eye movement metrics suggesting that researchers should consider the Simulation Theory differences as much as the search for congruence and reinforces the idea of combining techniques such as TMS with eye gaze methods. The overly simplistic view that the brain processes motor information across simulation states in exactly the same way has not helped to progress the understanding of motor cognition. In addition, future research will need to examine the meaning of the congruent-incongruent data. For example, increased MEPs during AO can reflect motor facilitation and motor inhibition – the same may be true for some of the eye gaze metrics and this remains an interesting area of investigation.

The main finding that AO had more eye gaze metric similarity than MI provided support for those who have raised concerns with the neural congruence mechanism as an explanation for MI effects (see review discussed in Chapter Two by Holmes & Calmels, 2008). The findings from this study informed the development of the design for the work reported in Chapter Four. Understanding the influence of speed and accuracy constraints on eye gaze metrics was important to many of the methodological considerations with older adult populations. The muscle atrophy effects associated with ageing could be expected to alter movement execution due to changes in muscle force afference through golgi tendon and muscle spindle proprioception and there is an extensive literature on this ageing effect (for a review see Narici & Maganaris, 2007). If planned MT is coded within the motor representation from felt muscle force (Jeannerod, 1994) then alterations to peripheral muscle structures and incongruence with central representations of the movement pattern are likely to alter MTs as was found in this study. More research in combination with other markers of muscle force (e.g., EMG, ultrasound scans) combined with eye movement metrics and chronometry may be able to provide further understanding of this complex age-related phenomenon. The increase in the MT by the older group highlighted an important issue related to behavioural matching and informed directly the management of video timing within the App design. Brain damage caused by stroke, for example, may leave the individual with significantly slowed motor function and determining the ‘matched’ video speed for an individual at a given time that could be altered for motor improvement was important for both theoretical and patient adherence concerns.

Of particular interest to this research programme was whether any of these physiological changes would be manifest in the eye movement metrics during AE and how any changes would transfer to AO and MI conditions. The finding that the covert conditions were not constrained in the same way as AE was particularly important and has wide-ranging implications for patients and clinicians. In older adults, AO and MI retained many of the spatial and temporal characteristics of a task and this was particularly the case for AO. If motor function decline is primarily peripheral, then limiting the extent to which ineffective motor activity influences the motor representation would seem sensible. If, as indicated by the programme's research findings, some of the eye movements in AO and MI are not differentiated by age, then regular practice with these covert techniques may slow the rate of motor function decline. The findings from the study reported in Chapter Four also indicated some age-related decline in eye movements that were consistent across AE, AO and MI. These finding suggest that there may be opportunities to modify ineffective eye movements in AE through AO and MI. This could be particularly useful in older populations where mentally simulating a movement with optimal eye gaze could lead to more functional eye gaze in AE thereby removing risk of trips or falls. The use of visual cues to relearn effective gaze strategies is clearly important and was fed into the design of the AST reported in Chapter Six.

Corroborating the results from Chapter Three the other important finding from Chapter Four was the dissimilar eye movements between AO and MI. In AO (1PP), the eye movements were found to be temporally and spatially similar to those executed in AE whereas in MI (1PP) the eye movements were only spatially similar. In Chapters Three and Four, however, the actions were simulated in a 1PP only and this raised the question of whether the dissimilar gaze between AO and MI also existed in 3PP. It was this concern, together with the lack of literature testing visual perspective and eye movements directly, and the knowledge that egocentric and allocentric position could significantly influence neural activity that informed the development of the study reported in Chapter Five. The data analysis in this study was novel and created specifically for this programme of work and allowed, for the first time, eye gaze to be used to comprehensively quantify MI in the1PP and 3PP. The main finding was that information relating to social gaze in AO (3PP) was not represented similarly during MI (3PP). If social gaze is a human evolutionary trait associated with empathy and action and intention understanding, then its absence during MI supports the idea that actions are interpreted in AO and represented (but not reinterpreted) in MI (Pylyshyn, 2003). If this is true, it may be important for individuals to attend to the correct spatial and temporal cues during AO so that the critical action information can be acquired and represented in subsequent MI.

The empirical studies reported from across Chapters Three to Five have, throughout the critical and analytical discussions, made reference to the implications and applications of the theoretical work. The vision was always to ensure that the research was meaningful, practical, and accessible. With the Higher Education Funding Council for England’s focus on research impact, this research programme, from its inception, aimed to have impact reach and significance. It was for these reasons that the final study sought additional funding from the university to develop a fully-integrated AO-MI toolkit that could draw on the findings of the empirical studies reported in this thesis. In addition, the intuitive, scientifically-rigorous toolkit brought together best practice MI and AO and had, as its fundamental theoretical basis, Jeannerod’s Simulation Theory. The AST toolkit is ready to be taken forward and tested in a feasibility RCT and a future aim will be to make the package available in the public domain. Additional components of the AST toolkit are likely to include: more complex, bimanual tasks; the ability to adjust image size; and, action videos filmed from a variety of angles.

This thesis has reported, for the first time, a series of studies that have considered the congruence of AE, AO and MI though a range of eye movement markers in a single paradigm. Twenty years after he first proposed the Simulation Theory, the results provide substantial support for Jeannerod’s ideas although, with the advantage of advanced eye gaze technology, the detail in the extent of the neural equivalence can be seen. If eye gaze research is embedded in more comprehensive designs with fMRI, TMS and EEG, our understanding of the brain’s control of movement will be far richer.

8 References

Abrams, R. A., Meyer, D. E., & Kornblum, S. (1990). Eye-hand coordination: Oculomotor control in rapid aimed limb movements. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 248-267. doi: 10.1037/0096-1523.16.2.248

Ambrosini, E., Costantini, M., & Sinigaglia, C. (2011). Grasping with the eyes. *Journal of Neurophysiology*, *106,* 1437-1442. doi: 10.1152/jn.00118.2011

Ambrosini, E., Sinigaglia, C., & Costantini, M. (2012). Tie my hands, tie my eyes. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(2), 263. doi: 10.1037/a0026570

Andersen, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual Review of Neuroscience, 20,* 303-330. doi: 10.1146/annurev.neuro.20.1.303

Badia, S. B. I., & Cameirao, M. S. (2012). The neurorehabilitation training toolkit (ntt): a novel worldwide accessible motor training approach for at-home rehabilitation after stroke. *Stroke Research and Treament*, *Article ID 802157*, 1-13. doi: 10.1155/2012/802157

Ballard, D. H., Hayhoe, M.M., & Pelz, J. B. (1995). Memory representations in natural tasks. *Journal of Cognitive Neuroscience*, *7*(1), 66-80. doi: 10.1162/jocn.1995.7.1.66

Bandura, A. (1962). Social learning through imitation. In M. R. Jones (Ed.), *Nebraska symposium on motivation*. Lincoln, NE: University of Nebraska Press.

Bandura, A. (1986). *Social foundations of thought and action*. Englewood Cliffs, NJ.

Barclay-Goddard, R., Stevenson, T., Thalman, L., & Poluha, W. (2011). Mental practice for treating upper extremity deficits in individuals with hemiparesis after stroke. *Stroke*, *42*(11), e574-e575. doi: 10.1161/STROKEAHA.111.627414

Berger, S. M., Carli, L.L., Hammersla, K. S., Karshmer, J. F., & Sanchez, M. E. (1979). Motoric and symbolic mediation in observational learning. *Journal of Personality and Social Psychology*, *37*(5), 735. doi: 10.1037/0022-3514.37.5.735

Bernardi, N. F., De Buglio, M., Trimarchi, P. D., Chielli, A., & Bricolo, E. (2013). Mental practice promotes motor anticipation: evidence from skilled music performance. *Frontiers in Human Neuroscience*, *7*, 451. doi: 10.3389/fnhum.2013.00451

Bienkiewicz, M. M., Rodger, M. W., Young, W. R., & Craig, C. M. (2013). Time to get a move on: Overcoming bradykinetic movement in Parkinson's disease with artificial sensory guidance generated from biological motion. *Behavioural Brain Research*, *253*, 113-120. doi: 10.1016/j.bbr.2013.07.003

Bland, J. M., & Altman, D. G. (1995). Calculating correlation coefficients with repeated observations: Part 1 - correlation within subjects. *British Medical Journal*, *310*, 446. doi: 10.1136/bmj.310.6977.446

Borst, G., & Kosslyn, S. M. (2008). Visual mental imagery and visual perception: Structural equivalence revealed by scanning processes. *Memory & Cognition*, *36*(4), 849-862. doi: 10.3758/MC.36.4.849

Bovend'Eerdt, T. J., Dawes, H., Sackley, C., Izadi, H., & Wade, D. T. (2010). An integrated motor imagery program to improve functional task performance in neurorehabilitation: a single-blind randomized controlled trial. *Archives of Physical Medicine and Rehabilitation, 91*(6), 939-946. doi: 10.1016/j.apmr.2010.03.008

Brady, N., Maguinness, C., & Choisdealbha, A.N. (2011). My hand or yours? Markedly different sensitivity to egocentric and allocentric views in the hand laterality task. *PLoS One, 6*(8), e23316. doi: 10.1371/journal.pone.0023316.g001

Brandt, S. A., & Stark, L. W. (1997). Spontaneous eye movements during visual imagery reflect the content of the visual scene. *Journal of Cognitive Neuroscience, 9,* 27-38. doi: 10.1162/jocn.1997.9.1.27

Brass, M., Bekkering, H., & Prinz, W. (2001). Movement observation affects movement execution in a simple response task. *Acta Psychologica, 106,* 3-22. doi: 10.1016/S0001-6918(00)00024-X

Briggs, S. D., Raz, N., & Marks, W. (1999). Age-related deficits in generation and manipulation of mental images: I. The role of sensorimotor speed and working memory. *Psychology and Aging*, *14*(3), 427. doi: 10.1037/0882-7974.14.3.427

Brouwer, A. M., Franz, V. H., & Gegenfurtner, K. R. (2009). Differences in fixations between grasping and viewing objects. *Journal of Vision*, *9*(1), 18 11-24. doi: 10.1167/9.1.18

Brown, B. B. (1968). Visual recall ability and eye movements. *Psychophysiology*, *4*(3), 300-306. doi: 10.1111/j.1469-8986.1968.tb02771.x

Brown, R., Kemp, U., & Macefield, V. (2013). Increase in muscle sympathetic nerve activity, heart rate, respiration, and skin blood flow during passive viewing of exercise. *Frontiers in Neuroscience*, *7*(102), 1-6. doi: 10.3389/fnins.2013.00102

Butler, A. J., & Page, S. J. (2006). Mental practice with motor imagery: evidence for motor recovery and cortical reorganization after stroke. *Archives of Physical Medicine and Rehabilitation*, *87*(12), 2-11.

Byrne, R. W., & Russon, A. E. (1998). Learning by imitation: a hierarchical approach. *Behavioral and Brain Sciences, 21*(5), 667-684. doi: 10.1016/j.apmr.2006.08.326

Caeyenberghs, K., Wilson, P. H., van Roon, D., Swinnen, S. P., & Smits-Engelsman, B. C. (2009). Increasing convergence between imagined and executed movement across development: evidence for the emergence of movement representations. *Developmental Science*, *12*(3), 474-483. doi: 10.1111/j.1467-7687.2008.00803.x

Callow, N., & Hardy, L. (2004). The relationship between the use of kinaesthetic imagery and different visual imagery perspectives. *Journal of Sports Sciences*, *22*(2), 167-177. doi: 10.1080/02640410310001641449

Calmels, C., Holmes, P., Lopez, E., & Naman, V. (2006). Chronometric comparison of actual and imaged complex movement patterns. *Journal of Motor Behavior*, *38*(5), 339-348. doi: 10.3200/JMBR.38.5.339-348

Calvo-Merino, B., Grezes, J., Glaser, D. E., Passingham, R. E., & Haggard, P. (2006). Seeing or doing? Influence of visual and motor familiarity in action observation. *Current Biology*, *16*(19), 1905-1910. doi: 10.1016/j.cub.2006.07.065

Cameirao, M. S., Badia, S. B., Oller, E. D., & Verschure, P. F. (2010). Neurorehabilitation using the virtual reality based Rehabilitation Gaming System: methodology, design, psychometrics, usability and validation. *Journal of Neuroengineering and Rehabilitation, 7*, 48. doi: 10.1186/1743-0003-7-48

Casile, A., Dayan, E., Caggiano, V., Hendler, T., Flash, T., & Giese, M. A. (2010). Neuronal encoding of human kinematic invariants during action observation. *Cerebral Cortex*, *20*(7), 1647-1655. doi: 10.1093/cercor/bhp229

Caspers, S., Zilles, K., Laird, A.R., & Eickhoff, S.B. (2010). A meta-analysis of action observation and imitation in the human brain. *NeuroImage, 50*(3), 1148-1167. doi: 10.1016/j.neuroimage.2009.12.112

Castiello, U. (2003). Understanding other people's actions: intention and attention. *Journal of Experimental Psychology, 29*(2), 416-430.

Causer, J, Janelle, C, Vickers, J, & Williams, M. (2012). Perceptual expertise: What can be trained? In N. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport: Research, theory & practice* (pp. 306-324). Oxon, UK: Routledge

Causer, J., McCormick, S. A., & Holmes, P. S. (2013). Congruency of gaze metrics in action, imagery and action observation. *Frontiers in Human Neuroscience*, *7*(604), 1-8. doi: 10.3389/fnhum.2013.00604

Chapman, G. J., & Hollands, M. A. (2006). Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion. *Gait & Posture*, *24*(3), 288-294. doi: 10.1016/j.gaitpost.2005.10.002

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* 2nd Ed. Hillsdale, NJ: Erlbaum.

Collet, C., Di Rienzo, F., El Hoyek, N., & Guillot, A. (2013). Autonomic nervous system correlates in movement observation and motor imagery. *Frontiers in Human Neuroscience, 7,* 1-17. doi: 10.3389/fnhum.2013.00415

Collet, C., Guillot, A., Lebon, F., MacIntyre, T., & Moran, A. (2011). Measuring motor imagery using psychometric, behavioral, and psychophysiological tools. *Exercise and Sport Sciences Reviews, 39*, 85-92. doi: 10.1097/JES.0b013e31820ac5e0

Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., . . . Van Essen, D. C. (1998). A common network of functional areas for attention and eye movements. *Neuron*, 21(4), 761-773. doi: 10.1016/S0896-6273(00)80593-0

Cotti, J., Guillaume, A., Alahyane, N., Pelisson, D., & Vercher, J. L. (2007). Adaptation of voluntary saccades, but not of reactive saccades, transfers to hand pointing movements. *Journal of Neurophysiology, 98*(2), 602-612. doi: 10.1152/jn.00293.2007

Crowdy, K. A., Kaur-Mann, D., Cooper, H. L., Mansfield, A. G., Offord, J. L., & Marple-Horvat, D.E. (2002). Rehearsal by eye movement improves visuomotor performance in cerebellar patients. *Experimental Brain Research, 146*(2), 244-247. doi: 10.1007/s00221-002-1171-0

Cui, X., Jeter, C. B., Yang, D., Montague, P. R., & Eagleman, D. M. (2007). Vividness of mental imagery: individual variability can be measured objectively. *Vision Research, 47*(4), 474-478. doi: 10.1016/j.visres.2006.11.013

Culham, J. C., Brandt, S. A., Cavanagh, P., Kanwisher, N. G., Dale, A. M., & Tootell, R. (1998). Cortical fMRI activation produced by attentive tracking of moving targets. *Journal of Neurophysiology, 80*(5), 2657-2670.

Cumming, J., Clark, S. E, Ste-Marie, D. M, McCullagh, P., & Hall, C. (2005). The functions of observational learning questionnaire (FOLQ). *Psychology of Sport and Exercise, 6*(5), 517-537. doi: 10.1016/j.psychsport.2004.03.006

Darling, W. G., Cooke, J. D., & Brown, S. H. (1989). Control of simple arm movements in elderly humans. *Neurobiology of Aging, 10*(2), 149-157. doi: 10.1016/0197-4580(89)90024-9

de Vries, S., & Mulder, T. (2007). Motor imagery and stroke rehabilitation: a critical discussion. *Journal of Rehabilitation Medicine, 39*(1), 5-13. doi: 10.2340/16501977-0020

Debarnot, U., Valenza, G., Champely, S., Scilingo, E. P., De Rossi, D., & Guillot, A. (2011). Motor imagery effectiveness for mirror reversed movements. *Cognitive, Affective & Behavioral Neuroscience, 11*(1), 22-31. doi: 10.3758/s13415-010-0008-8

Decety, J. (1996a). The neurophysiological basis of motor imagery. *Behavioural Brain Research, 77*(1), 45-52. doi: 10.1016/0166-4328(95)00225-1

Decety, J. (1996b). Do imagined and executed actions share the same neural substrate? *Cognitive Brain Research, 3*(2), 87-93. doi: 10.1016/0926-6410(95)00033-X

Decety, J., & Grèzes, J. (1999). Neural mechanisms subserving the perception of human actions. *Trends in Cognitive Sciences, 3*(5), 172-178. doi: 10.1016/S1364-6613(99)01312-1

Decety, J., & Sommerville, J. A. (2003). Shared representations between self and other: a social cognitive neuroscience view. *Trends in Cognitive Sciences, 7*(12), 527-533. doi: 10.1016/j.tics.2003.10.004

Decety, J., Jeannerod, M., & Prablanc, C. (1989). The timing of mentally represented actions. *Behavioural Brain Research, 34*(1), 35-42. doi: 10.1016/S0166-4328(89)80088-9

Decety, J., Jeannerod, M., Germain, M., & Pastene, J. (1991). Vegetative response during imagined movement is proportional to mental effort. *Behavioural Brain Research, 42*(1), 1-5. doi: 10.1016/S0166-4328(05)80033-6

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4*(11), 423-431. doi: 10.1016/S1364-6613(00)01537-0

Desmurget, M., Epstein, C. M., Turner, R.S., Prablanc, C., Alexander, G.E., & Grafton, S.T. (1999). Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neuroscience, 2*(6), 563-567. doi: 10.1038/9219

Di Fabio, R. P., Greany, J. F., & Zampieri, C. (2003). Saccade-stepping interactions revise the motor plan for obstacle avoidance. *Journal of Motor Behavior, 35*(4), 383-397. doi: 10.1080/00222890309603158

Di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (1992). Understanding motor events: a neurophysiological study. *Experimental Brain Research, 91*(1), 176-180. doi: 10.1007/BF00230027

Dickstein, R., Gazit-Grunwald, M., Plax, M., Dunsky, A., & Marcovitz, E. (2005). EMG activity in selected target muscles during imagery rising on tiptoes in healthy adults and poststrokes hemiparetic patients. *Journal of Motor Behavior, 37*(6), 475-483. doi: 10.3200/JMBR.37.6.475-483

Dohle, C., Püllen, J., Nakaten, A., Küst, J., Rietz, C., & Karbe, H. (2009). Mirror therapy promotes recovery from severe hemiparesis: a randomized controlled trial. *Neurorehabilitation and Neural Repair, 23(3),* 209-217. doi: 10.1177/1545968308324786

Doolittle, N. D. (1992). The experience of recovery following lacunar stroke. *Rehabilitation Nursing, 17*(3), 122-126. doi: 10.1002/j.2048-7940.1992.tb01528.x

Dror, I. E., & Kosslyn, S. M. (1994). Mental imagery and aging. *Psychology and Aging, 9*(1), 90. doi: 10.1037/0882-7974.9.1.90

Edwards, M. G., Humphreys, G. W., & Castiello, U. (2003). Motor facilitation following action observation: A behavioural study in prehensile action. *Brain and Cognition, 53*(3), 495-502. doi: 10.1016/s0278-2626(03)00210-0

Eggermont, L. H. P., Knol, D. L., Hol, E. M., Swaab, D. F., & Scherder, E. J. A. (2009). Hand motor activity, cognition, mood, and the rest–activity rhythm in dementia: A clustered RCT. *Behavioural Brain Research, 196*(2), 271-278. doi: 10.1016/j.bbr.2008.09.012

Elliott, D., Hayes, S. J., & Bennett, S. J. (2012). 125 years of perceptual-motor skill research. *The American Journal of Psychology, 125*(1), 9-23. doi: 10.5406/amerjpsyc.125.1.0009

Ertelt, D., Small, S., Solodkin, A., Dettmers, C., McNamara, A., Binkofski, F., & Buccino, G. (2007). Action observation has a positive impact on rehabilitation of motor deficits after stroke. *NeuroImage, 36*(Suppl 2), T164-173. doi: 10.1016/j.neuroimage.2007.03.043

Eskenazi, T., Rotshtein, P., Grosjean, M., & Knoblich, G. (2012). The neural correlates of Fitts's law in action observation: an fMRI study. *Social Neuroscience, 7*(1), 30-41. doi: 10.1080/17470919.2011.576871

Ewan, L. M., Smith, N. C., & Holmes, P. S. (2010). Disruption to Aspects of Imagery Vividness following Stroke. *Journal of Mental Imagery, 34*(3), 3-14.

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion, 7*(2), 336. doi: 10.1037/1528-3542.7.2.336

Farah, M. J., Soso, M. J., & Dasheiff, R. M. (1992). Visual angle of the mind's eye before and after unilateral occipital lobectomy. *Journal of Experimental Psychology: Human Perception and Performance, 18*(1), 241. doi: 10.1037/0096-1523.18.1.241

Febretti, A., & Garzotto, F. (2009). *Usability, playability, and long-term engagement in computer games*. Paper presented at the 27th International Conference on Human Factors in Computing System, New York, NY.

Feltz, D., & Landers, A. (2007). The effects of mental practice on motor skill learning and performance: A meta-analysis. *Journal of Sport Psychology, 5*, 25-57.

Filimon, F, Nelson, J. D., Hagler, D. J., & Sereno, M. I. (2007). Human cortical representations for reaching: mirror neurons for execution, observation, and imagery. *NeuroImage, 13(*4), 1315-1328. doi: v10.1016/j.neuroimage.2007.06.008

Findlay, J. M., & Gilchrist, I. D. (1998). Eye guidance and visual search. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 295-312). Oxford, England: Elsevier. doi: 10.1016/B978-008043361-5/50014-6

Finke, R. A. (1989). *Principles of mental imagery*. Cambridge, MA: The MIT Press.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*(6), 381. doi: 10.1037/h0055392

Flanagan, J. R., & Johansson, R. S. (2003). Action plans used in action observation. *Nature, 24*, 769-771. doi: 10.1038/nature01861

Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavioural Research Methods, Instruments, & Computers, 35*(1), 116-124. doi: 10.3758/BF03195503

Fourkas, A. D., Ionta, S., & Aglioti, S. M. (2006). Influence of imagined posture and imagery modality on corticospinal excitability. *Behavioural Brain Research, 168*(2), 190-196. doi: 10.1016/j.bbr.2005.10.015

Franceschini, M., Ceravolo, M. G., Agosti, M., Cavallini, P., Bonassi, S., Dall'Armi, V., . . . Sale, P. (2012). Clinical Relevance of Action Observation in Upper-Limb Stroke Rehabilitation A Possible Role in Recovery of Functional Dexterity. A Randomized Clinical Trial. *Neurorehabilitation and Neural Repair, 26*(5), 456-462. doi: 10.1177/1545968311427406

Fugl-Meyer, A. R., Jääskö, L., Leyman, I., Olsson, S., & Steglind, S. (1974). The post-stroke hemiplegic patient: A method for evaluation of physical performance. *Scandinavian Journal of Rehabilitation Medicine,* 7(1), 13-31.

Gabbard, C., Cacola, P., & Bobbio, T. (2011). Examining age-related movement representations for sequential (fine-motor) finger movements. *Brain and Cognition, 77*(3), 459-463. doi: 10.1016/j.bandc.2011.08.011

Gallese, V., & Goldman, A. (1998). Mirror neurons and the simulation theory of mind-reading. *Trends in Cognitive Sciences, 2*(12), 493-501. doi: 10.1016/S1364-6613(98)01262-5

Garrison, K. A., Winstein, C. J., & Aziz-Zadeh, L. (2010). The mirror neuron system: a neural substrate for methods in stroke rehabilitation. *Neurorehabilitation and Neural Repair, 24*(5), 404-412. doi: 10.1177/1545968309354536

Gesierich, B., Bruzzo, A., Ottoboni, G., & Finos, L. (2008). Human gaze behaviour during action execution and observation. *Acta Psychologica, 128*(2), 324-330. doi: 10.1016/j.actpsy.2008.03.006

Ghez, C., Scheidt, R., & Heijink, H. (2007). Different learned coordinate frames for planning trajectories and final positions in reaching. *Journal of Neurophysiology, 98*(6), 3614-3626. doi: 10.1152/jn.00652.2007

Glisky, M., Williams, G., & Kihlstrom, J. (1996). Internal and external mental imagery perspectives and performance on two tasks. *Journal of Sport Behaviour, 19,* 3-18.

Goggin, N. L., & Meeuwsen, H. J. (1992). Age-related differences in the control of spatial aiming movements. *Research Quarterly for Exercise and Sport, 63*(4), 366-372. doi: 10.1080/02701367.1992.10608758

Goginsky, A.M., & Collins, D. (1996). Research design and mental practice. *Journal of Sports Sciences, 14*(5), 381-392. doi: 10.1080/02640419608727725

Goldenberg, G. (1992). Loss of visual imagery and loss of visual knowledge - a case study. *Neuropsychologia, 30*(12), 1081-1099. doi: 10.1016/0028-3932(92)90100-Z

Goodale, M, A., & Milner, A.D. (1992). Separate visual pathways for percpetion and action. *Trends in Neurosciences, 15*, 20-25. doi: 10.1016/0166-2236(92)90344-8

Goransson, B., Gulliksen, J., & Boivie, I. (2003). The usability design process - integrating user-centered systems design in the software development process. *Software Process Improvement and Practice, 8*, 11-131. doi: 10.1002/spip.174

Grafton, S. T., Arbib, M. A., Fadiga, L., & Rizzolatti, G. (1996). Localization of grasp representations in humans by positron emission tomography. *Experimental Brain Research, 112*, 103-111. doi: 10.1007/BF00227183

Grant, E. R., & Spivey, M. J. (2003). Eye movements and problem solving guiding attention guides thought. *Psychological Science, 14*(5), 462-466. doi: 10.1111/1467-9280.02454

Gregg, M., Hall, C., & Butler, A. (2010). The MIQ-RS: a suitable option for examining movement imagery ability. *Evidence-Based Complementary and Alternative Medicine, 7*(2), 249-257. doi: 10.1093/ecam/nem170

Grèzes, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verb generation of actions: A meta-analysis. *Human Brain Mapping, 12*, 1-19. doi: 10.1002/1097-0193(200101)12:1<1::AID-HBM10>3.0.CO;2-V

Griffin, Z. M., & Bock, K. (2000). What the eyes say about speaking. *Psychological Science, 11*(4), 274-279. doi: 10.1111/1467-9280.00255

Grosjean, M., Shiffrar, M., & Knoblich, G. (2007). Fitts's law holds for action perception. *Psychological Science, 18*(2), 95-99. doi: 10.1111/j.1467-9280.2007.01854.x

Gueugneau, N., Crognier, L., & Papaxanthis, C. (2008). The influence of eye movements on the temporal features of executed and imagined arm movements. *Brain Research, 1187*, 95-102. doi: 10.1016/j.brainres.2007.10.042

Guillot, A., & Collet, C. (2005a). Contribution from neurophysiological and psychological methods to the study of motor imagery. *Brain Research Reviews, 50*(2), 387-397. doi: 10.1016/j.brainresrev.2005.09.004

Guillot, A., & Collet, C. (2005b). Duration of mentally simulated movement: A review. *Journal of Motor Behavior, 37*(1), 10-20. doi: 10.3200/JMBR.37.1.10-20

Guillot, A., Lebon, F., Rouffet, D., Champely, S., Doyon, J., & Collet, C. (2007). Muscular responses during motor imagery as a function of muscle contraction types. *International Journal of Psychophysiology, 66*(1), 18-27. doi: 10.1016/j.ijpsycho.2007.05.009

Guillot, A., Moschberger, K., & Collet, C. (2013). Coupling movement with imagery as a new perspective for motor imagery practice. *Behavioural and Brain Functions*, *9*(8), 1-8.

Gulliksen, J., Göransson, B., Boivie, Inger, Blomkvist, S., Persson, J., & Cajander, Å. (2003). Key principles for user-centred systems design. *Behaviour & Information Technology, 22*(6), 397-409. doi: 10.1080/01449290310001624329

Hagemann, N., Strauss, B., & Canal-Bruland, R. (2006). Training perceptual skill by orienting visual attention. *Journal of Sport & Exercise Psychology, 28*, 143-158.

Hale, B., Raglin, J.S., & Koceja, D.M. (2003). Effect of mental imagery of a motor task on the Hoffmann reflex. *Behavioural Brain Research, 142*(1), 81-87. doi: 10.1016/S0166-4328(02)00397-2

Hale, B. D. (1982). The effects of internal and external imagery on muscular and ocular concomitants. *Journal of Sport Psychology, 4*(4), 379-387.

Hardwick, R.M., McAllister, C.J., Holmes, P.S., & Edwards, M.G. (2012). Transcranial magnetic stimulation reveals modulation of corticospinal excitability when observing actions with the intention to imitate. *European*

Journal of Neuroscience, 35(9), 1475-1480. doi: 10.1111/j.1460-9568.2012.08046.x

Hardy, L. (1997). Three myths in applied consultancy work. *Journal of Applied Sport Psychology, 9,* 277-294. doi: 10.1080/10413209708406487

Hardy, L., & Callow, N. (1999). Efficacy of external and internal visual imagery perspectives for the enhancement of performance on tasks in which form is important. *Journal of Sport & Exercise Psychology, 21*(2), 95-112.

Harle, S. K., & Vickers, J. N. (2001). Training quiet eye improves accuracy in basketball free throw. *The Sport Psychologist, 15*, 289-305.

Haslinger, B., Erhard, P., Altenmüller, E., Schroeder, U, Boecker, H., & Ceballos-Baumann, A. O. (2005). Transmodal sensorimotor networks during action observation in professional pianists. *Journal of Cognitive Neuroscience, 17*(2), 282-293. doi: 10.1162/0898929053124893

Hayes, S. J., Elliott, D., & Bennett, S. J. (2013). Visual online control processes are acquired during observational practice. *Acta Psychologica, 143*(3), 298-302. doi: 10.1016/j.actpsy.2013.04.012

Hayhoe, M. (2004). Advances in relating eye movements and cognition. *Infancy, 6*(2), 267-274. doi: 10.1207/s15327078in0602_7

Hayhoe, M., & Ballard, D. (2005). Eye movements in natural behavior. *Trends in Cognitive Sciences, 9(*4), 188-194. doi: 10.1016/j.tics.2005.02.009

Hebb, D. O. (1968). Concerning imagery. *Psychological Review, 75*(6), 466. 10.1037/h0026771

Hecker, J. E., & Kaczor, L. M. (1988). Application of imagery theory to sport psychology: Some preliminary findings. *Journal of Sport & Exercise Psychology, 10*(4), 363.

Helsen, W. F., Elliott, D., Starkes, J. L., & Ricker, K. L. (1998). Temporal and spatial coupling of point of gaze and hand movements in aiming. *Journal of Motor Behavior, 30*(3), 249-259. doi: 10.1080/00222899809601340

Henderson, J. M. (2003). Human gaze control during real-world scene perception. *Trends in Cognitive Sciences, 7*(11), 498-504. doi: 10.1016/j.tics.2003.09.006

Heremans, E., Helsen, W. F., & Feys, P. (2008). The eyes as a mirror of our thoughts: quantification of motor imagery of goal-directed movements through eye movement registration. *Behavioural Brain Research, 187*(2), 351-360. doi: 10.1016/j.bbr.2007.09.028

Heremans, E., Helsen, W. F., De Poel, H. J., Alaerts, K., Meyns, P., & Feys, P. (2009). Facilitation of motor imagery through movement-related cueing. *Brain Research, 1278*, 50-58. doi: 10.1016/j.brainres.2009.04.041

Heremans, E., Nieuwboer, A., Feys, P., Vercruysse, S., Vandenberghe, W., Sharma, N., & Helsen, W. (2012a). External cueing improves motor imagery quality in patients with Parkinson's disease. *Neurorehabilitation and Neural Repair, 26*(1), 27-35. doi: 10.1177/1545968311411055

Heremans, E., Nieuwboer, A., Spildooren, J., De Bondt, S., D'Hooge A, M., Helsen, W., & Feys, P. (2012b). Cued motor imagery in patients with multiple sclerosis. *Neuroscience, 206*, 115-121. doi: 10.1016/j.neuroscience.2011.12.060

Heremans, E., Smits-Engelsman, B., Caeyenberghs, K., Vercruysse, S., Nieuwboer, A., Feys, P., & Helsen, W. F. (2011). Keeping an eye on imagery: the role of eye movements during motor imagery training. *Neuroscience, 195*, 37-44. doi: 10.1016/j.neuroscience.2011.07.030

Hesse, C., de Grave, D. D., Franz, V. H., Brenner, E., & Smeets, J. B. (2008). Planning movements well in advance. *Cogitive Neuropsychology, 25*(7-8), 985-995. doi: 10.1080/02643290701862399

Heyes, C. (2001). Causes and consequences of imitation. *Trends in Cognitive Sciences*, 5(6), 253-261. doi: 10.1016/S1364-6613(00)01661-2

Hickok, G. (2009). Eight problems for the mirror neuron theory of action understanding in monkeys and humans. *Journal of Cognitive Neuroscience, 21*(7), 1-15. doi: 10.1162/jocn.2009.21189

Holden, K. (2005). Virtual environments for motor rehabiliation: review. *CyberPsychology and Behaviour, 8,* 187-219. doi: 10.1089/cpb.2005.8.187

Holmes, P. S. (2007). Theoretical and practical problems for imagery in stroke rehabilitation: An observation solution. *Rehabilitation Psychology, 52*(1), 1-10. doi: 10.1037/0090-5550.52.1.1

Holmes, P. S. (2012). Double default: time to develop a different perspective? *Jounal of Mental Imagery, 36*(1), 53-58.

Holmes, P. S., & Calmels, C. (2008). A neuroscientific review of imagery and observation use in sport. *Journal of Motor Behavior, 40*, 433-445. doi: 10.3200/JMBR.40.5.433-445

Holmes, P.S., & Calmels, C. (2011). Mental practice: Neuroscientific support for a new approach. In D. Collins, A. Abbott & H. Richards (Eds.), *Performance psychology: A practioner's guide* (pp. 231-244). London: Elsevier. doi: 10.1016/B978-0-443-06734-1.00016-X

Holmes, P. S., & Collins, D. J. (2001). The PETTLEP approach to motor imagery: A functional equivalence model for sport psychologists. *Journal of Applied Sport Psychology, 13*(1), 60-83. doi: 10.1080/10413200109339004

Holmes, P. S., & Collins, D.J. (2002). Functional equivalence solutions for problems with motor imagery. In I. M. Cockerill (Ed.), *Solutions in sports psychology* (pp. 120-140). UK: Cengage Learning.

Holmes, P. S., Collins, D. J., & Calmels, C. (2006). Electroencephalographic functional equivalence during observation of action. *Journal of Sports Sciences, 24*(06), 605-616. doi: 10.1080/02640410500244507

Holmes, P. S., Cumming, J., & Edwards, M. G. (2010). Movement imagery, observation, and skill. In A. Guillot & C. Collect (Eds.), *The neurophysiological foundations of mental and motor imagery* (pp. 253-270). Oxford, UK: Oxford University Press. doi: 10.1093/acprof:oso/9780199546251.003.0018

Holmes, P. S., & Ewan, L. M. (2007). The use of structured observation as a stroke rehabilitation aid: an opinion from neuroscience. *The British Journal of Occupational Therapy, 70*(10), 454-456.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J. (2011). *Eye tracking: A comprehensive guide to methods and measures*: Oxford University Press.

Huaman, A. G., & Sharpe, J. A. (1993). Vertical saccades in senescence. *Investigative Ophthalmology & Visual Science, 34*, 2588-2595.

Iacoboni, M., Molner-Szakacs, I. M., Gallese, V., Buccino, G., Mazziotta, J. C., & Rizzolatti, G. (2005). Grasping the intentions of others with one's own mirror neuron system. *PLoS Biology, 3*(3), e79. doi: 10.1371/journalpbio.0030079

Iacoboni, M., Woods, R. P., Brass, M., Bekkering, H., Mazziotta, J. C., & Rizzolatti, G. (1999). Cortical mechanisms of human imitation. *Science, 286*(5449), 2526-2528. doi: 10.1126/science.286.5449.2526

Ietswaart, M., Johnston, M., Dijkerman, H. C., Joice, S., Scott, C. L., MacWalter, R. S., & Hamilton, S. J. (2011). Mental practice with motor imagery in stroke recovery: randomized controlled trial of efficacy. *Brain, 134*(5), 1373-1386. doi: 10.1093/brain/awr077

Immenroth, M., Bürger, T., Brenner, J., Nagelschmidt, M., Eberspächer, H., & Troidl, H. (2007). Mental training in surgical education: a randomized controlled trial. *Annals of Surgery, 245*(3), 385. doi: 10.1097/01.sla.0000251575.95171.b3

Intercollegiate Stroke Working Party (2008). National clinical guideline for stroke (4th ed). London: Royal College of Physicians.

Ionta, S., Perruchoud, D., Draganski, B., & Blanke, O. (2012). Body context and posture affect mental imagery of hands. *PLoS One, 7*(3), e34382. doi: 10.1371/ journal.pone.0034382

Irving, E. L., Steinbach, M. J., Lillakas, L., Babu, R. J., & Hutchings, N. (2006). Horizontal saccade dynamics across the human life span. *Investigative Ophthalmology & Visual Science, 47*(6), 2478-2484. doi: 10.1167/iovs.05-1311

ISO (1999). ISO 13407: *Human-centred design processes for interactive systems.* Geneva: International Standards Organisation.

Jacobson, E. (1932). Electrophysiology of mental activities. *The American Journal of Psychology, 44*(4), 677-694. doi: 10.2307/1414531

Jeannerod, M. (1986). Mechanims of visuomotor coordination: A study in normal and brain-damaged subjects. *Neuropsychologia, 24*(1), 41-78. doi: 10.1016/0028-3932(86)90042-4

Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences, 17,* 187-245. doi: 10.1017/S0140525X00034026

Jeannerod, M. (1997). *The cognitive neuroscience of action*: Oxford, UK: Blackwell.

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. *NeuroImage, 14*(1), S103-S109. doi: 10.1006/nimg.2001.0832

Jeannerod, M., & Frak, V. (1999). Mental imaging of motor activitiies in humans. *Current Opinion in Neurobiology, 9*, 735-739. doi: 10.1016/S0959-4388(99)00038-0

Jeannerod, M., Jouvert, J., & Jouvert, M. (1962). Study of ocular movements observed in man in the course of waking and of sleep. *Comptes Rendus de la Société de Biologie, 156,* 1407-1410.

Johansson, R. S., Holsanova, J., & Holmqvist, K. (2005). *What do eye movements reveal about mental imagery? Evidence from visual and verbal elicitations*.

Paper presented at the Proceedings of the 27th Cognitive Science Conference, Stresa, Italy.

Johansson, R. S., Holsanova, J., & Holmqvist, K. (2010). *Eye movements during mental imagery are not reenactments of perception.* Paper presented at the Proceedings of the 32nd Cognitive Science Society Conference, Portland, Oregan.

Ketcham, C. J., Seidler, R. D., Van Gemmert, A. W., & Stelmach, G. E. (2002). Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *Journal of Gerontology: Psychological Sciences, 57*(1), P54-64. doi: 10.1093/geronb/57.1.P54

Khan, A., Franks, I.M., Elliott, D., Lawrence, G. P., Chua, R., Bernier, P.M., . . . Weeks, D.J. (2006). Inferring online and offline processing of visual feedback in target-directed movements from kinematic data. *Neuroscience and Biobehavioral Reviews, 30*, 1106-1121. doi: 10.1016/j.neubiorev.2006.05.002

Kim, H. (2013). Statistical notes for clinical researchers: assessing normal distribution (2) using skewness and kurtosis. *Restorative Dentistry & Endodontics, 38*(1), 52-54. doi: 10.5395/rde.2013.38.1.52

Kinoshita, H., & Francis, P. R. (1996). A comparison of prehension force control in young and elderly individuals. *European Journal of Applied Physiology and Occupational Physiology, 74*(5), 450-460. doi: 10.1007/BF02337726

Klein, C. S., Rice, C. L., & Marsh, G. D. (2001). Normalized force, activation, and coactivation in the arm muscles of young and old men. *Journal of Applied Physiology, 91*(3), 1341-1349.

Kosslyn, S. M. (1975). Information representation in visual images. *Cognitive Psychology, 7*(3), 341-370. doi: 10.1016/0010-0285(75)90015-8

Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: a computational approach. *Psychological Review, 94*(2), 148. doi: 10.1037/0033-295X.94.2.148

Kosslyn, S. M. (1993). Visual mental imagery activates topgraphically organized visual cortex: PET investigations. *Journal of Cognitive Neuroscience, 5*(3), 263-287. doi: 10.1162/jocn.1993.5.3.263

Kourtis, D., Sebanz, N., & Knoblich, G. (2012). EEG correlates of Fitts's law during preparation for action. *Psychological Research, 76*(4), 514-524. doi: 10.1007/s00426-012-0418-z

Kurtzer, I., Herter, T. M., & Scott, S. H. (2005). Random change in cortical load representation suggests distinct control of posture and movement. *Nature Neuroscience, 8*(4), 498-504. doi: 10.1038/nn1420

Laeng, B., & Teodorescu, D. (2002). Eye scanpaths during visual imagery reenact those of perception of the same visual scene. *Cognitive Science, 26*, 207-231. doi: 10.1207/s15516709cog2602_3

Land, M., Mennie, N., & Rusted, J. (1999). The roles of vision and eye movements in the control of activities of daily living. *Perception, 28*, 1311-1328. doi: 10.1068/p2935

Lang, P. J. (1979). A bio-informational theory of emotional imagery. *Psychophysiology, 16*(6), 495-512. doi: 10.1111/j.1469-8986.1979.tb01511.x

Lankford, C. (2000). Gaze Tracker: Software designed to facilitate eye movement analysis. In *Proceedings of the eye tracking applications research symposium* (pp. 57-63). New York: ACM Press.

Lawrence, G., Callow, N., & Roberts, R. (2013). Watch me if you can: imagery ability moderates observational learning effectiveness. *Frontiers in Human Neuroscience, 7(522), 1-7.* doi: 10.3389/fnhum.2013.00522

Lazzari, S., Mottet, D., & Vercher, J. (2009). Eye–hand coordination in rhythmical pointing. *Journal of Motor Behavior, 41*, 294-304. doi: 10.3200/JMBR.41.4.294-304

Leonard, G, & Tremblay, F. (2007). Corticomotor facilitation associated with observation, imagery and imitation of hand actions: a comparative study in young and old adults. *Experimental Brain Research, 177*, 167-175. doi: 10.1007/s00221-006-0657-6

Letesson, C., & Edwards, M. G. (2012). Eye-movements during transitive action observation: How does it inform us about the origin of the action priming effect? *Frontiers in Human Neuroscience. Conference Abstract: Belgian Brain Council.* doi: 10.3389/conf.fnhum.2012.210.00001

Liman, T. G., & Zangemeister, W. H. (2012). Scanpath eye movements during visual mental imagery in a simulated hemianopia paradigm. *Journal of Eye Movement Research, 5*(1)(2), 1-11.

Liu, K. P., Chan, C. C., Lee, T. M., & Hui-Chan, C. W. (2004). Mental imagery for promoting relearning for people after stroke: A randomized controlled trial. *Archives of Physical Medicine and Rehabilitation, 85*(9), 1403-1408. doi: 10.1016/j.apmr.2003.12.035

Loftus, G. R., & Mackworth, N. H. (1978). Cognitive determinants of fixation location during picture viewing. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 565-572. doi: 10.1037/0096-1523.4.4.565

Lorey, B., Bischoff, M., Pilgramm, S., Stark, R., Munzert, J., & Zentgraf, K. (2009). The embodied nature of motor imagery: the influence of posture and perspective. *Experimental Brain Research, 194*(2), 233-243. doi: 10.1007/s00221-008-1693-1

Lorey, B., Pilgramm, S., Walter, B., Stark, R., Munzert, J., & Zentgraf, K. (2010). Your mind's hand: motor imagery of pointing movements with different accuracy. *NeuroImage, 49*(4), 3239-3247. doi: 10.1016/j.neuroimage.2009.11.038

Lotze, M., Montoya, P., Erb, M., Hülsmann, E., Flor, H., Klose, U., . . . Grodd, W. (1999). Activation of cortical and cerebellar motor areas during executed and imagined hand movements: an fMRI study. *Journal of Cognitive Neuroscience, 11*(5), 491-501. doi: 10.1162/089892999563553

Lotze, M., & Zentgraf, K. (2010). Contribuiton of the primary motor cortex to motor imagery. In A. Guillot & C. Collet (Eds.), *The Neurophysiological foundations of mental imagery* (pp. 31-45). NY: Oxford University Press Inc. doi: 10.1093/acprof:oso/9780199546251.003.0003

Louis, M., Guillot, A., Maton, S., Doyon, J., & Collet, C. (2008). Effect of imagined movement speed on subsequent motor performance. *Journal of Motor Behavior, 40*(2), 117-132. doi: 10.3200/JMBR.40.2.117-132

Lyle, R. C. (1981). A performance test for assessment of upper limb function in physical rehabilitation treatment and research. *International Journal of Rehabilitation Research*, 4(4). 483-92. doi: 10.1097/00004356-198112000-00001

MacIntyre, T., Moran, A., Collet, C, Guillot, A., Campbell, M., Matthews, J., . . . Lowther, J. (2013). The BASES expert statement on the use of mental imagery in sport, exercise and rehabilitation contexts. *The Sport and Exercise Scientist*, Winter, 9-11.

Mackay, D. G. (1981). The problem of rehearsal or mental practice. *Journal of Motor Behavior, 13*(4), 274-285. doi: 10.1080/00222895.1981.10735253

Maclean, N., Pound, P., Wolfe, C., & Rudd, A. (2000). Qualitative analysis of stroke patients' motivation for rehabilitation. *British Medical Journal, 321*(7268), 1051. doi: 10.1136/bmj.321.7268.1051

Macuga, K. L., & Frey, S. H. (2011). Neural representations involved in observed, imagined, and imitated actions are dissociable and hierarchically organized. *NeuroImage, 59,* 2798-2807. doi: 10.1016/j.neuroimage.2011.09.083

Magill, R. A. (2000). *Motor learning: concepts and applications*. New York, NY: McGraw-Hill.

Maguire, M. (2001). Methods to support human-centred design. *International Journal of Human-Computer Studies*, *55*(4), 587-634. doi: 10.1006/ijhc.2001.0503

Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology, 41*, 365-378. doi: 10.1037/h0084157

Maruff, P., Wilson, P. H., De Fazio, J., Cerritelli, B., Hedt, A., & Currie, J. (1999). Asymmetries between dominant and non-dominant hands in real and imagined motor task performance. *Neuropsychologia, 37*(3), 379-384. doi: 10.1016/S0028-3932(98)00064-5

Mataric, M. J., & Pomplum, M. (1998). Fixation behaviour in observation and imitation of human movement. *Cognitive Brain Research, 7*, 191-202. doi: 10.1016/S0926-6410(98)00025-1

Mathiowetz, V., Volland, G., Kashman, N., & Weber, K. (1985). Adult norms for the Box and Block Test of manual dexterity. *American Journal of Occupational Therapy, 39*, 386-391. doi: 10.5014/ajot.39.6.386

McCormick, S. A., Causer, J., & Holmes, P. S. (2012). Eye gaze metrics reflect a shared motor representation for action observation and movement imagery. *Brain and Cognition, 80*(1), 83-88. doi: 10.1016/j.bandc.2012.04.010

McNevin, N., Wulf, G., & Carlson, C. (2000). Effects of attentional focus, self-control, and dyad training on motor learning: Implications for physical rehabilitation. *Physical Therapy, 80,* 373-385.

Meltzoff, A.N., & Moore, M.K. (1983). The origins of imitation in infancy: paradigm phenomena, and theories. *Advances in Infancy Research*, 2, 265-301.

Menon, R. S., & Kim, S. (1999). Spatial and temporal limits in cognitive neuroimaging with fMRI. *Trends in Cognitive Sciences, 3*(6), 207-216. doi: 10.1016/S1364-6613(99)01329-7

Michielsen, M. E., Selles, R. W., van der Geest, J.N., Eckhardt, M., Yavuzer, G., Stam, H. J., . . . Bussmann, J. B. J. (2011). Motor recovery and cortical reorganization after mirror therapy in chronic stroke patients a phase ii randomized controlled trial. *Neurorehabilitation and Neural Repair, 25*(3), 223-233. doi: 10.1177/1545968310385127

Moore, L. J., Vine, S. J., Cooke, A., Ring, C., & Wilson, M. R. (2012). Quiet eye training expedites motor learning and aids performance under heightened anxiety: the roles of response programming and external attention. *Psychophysiology, 49*(7), 1005-1015. doi: 10.1111/j.1469-8986.2012.01379.x

Moran, A. (2009). Cognitive psychology in sport: Progress and prospects. *Psychology of Sport and Exercise, 10*(4), 420-426. doi: 10.1016/j.psychsport.2009.02.010

Morris, T., Spittle, M., & Watt, A P. (2005). *Imagery in sport.* Champaign; IL: Human Kinetics.

Motter, B. C., & Belky, E. J. (1998). The zone of focal attention during active visual search. *Vision Research, 38*(7), 1007-1022. doi: 10.1016/S0042-6989(97)00252-6

Mottet, D., & Bootsma, R. .J. (1999). The dynamics of goal-directed rhythmical aiming. *Biological Cybernetics, 80*(4), 235-245. doi: 10.1007/s004220050521

Mottet, D., Guiard, Y., Ferrand, T., & Bootsma, R. J. (2001). Two-handed performnace of a rhythmical Fitts task by individuals and dyads. *Journal of Experimental Psychology: Human Perception and Performance, 27*(6), 1275-1286. doi: 10.1037/0096-1523.27.6.1275

Mulder, T., de Vries, S., & Zijlstra, S. (2005). Observation, imagination and execution of an effortful movement: more evidence for a central explanation of motor imagery. *Experimental Brain Research, 163*, 344-351. doi: 10.1007/s00221-004-2179-4

Mulder, T., Zijlstra, S., Zijlstra, W., & Hochstenbach, J. (2004). The role of motor imagery in learning a totally novel movement. *Experimental Brain Research, 154*(2), 211-217. doi: 10.1007/s00221-003-1647-6

Nakano, H., Ueta, K., Osumi, M., & Morioka, S. (2012). Brain activity during the observation, imagery, and execution of tool use: An fNIRS/EEG study. *Journal of Novel Physiotherapies, S1:009*. doi: 10.4172/2165-7025.s1-009

Narici, M. V. , & Maganaris, C. N. (2007). Plasticity of the muscle-tendon complex with disuse and aging. *Exercise and Sport Sciences Reviews, 35*(3), 126-134. doi: 10.1097/jes.0b013e3180a030ec

Nedelko, V., Hassa, T., Hamzei, F., Schoenfeld, M. A., & Dettmers, C. (2012). Action imagery combined with action observation activates more corticomotor regions than action observation alone. *Journal of Neurologic Physical Therapy, 36(*4), 182-188. doi: 10.1097/NPT.0b013e318272cad1

Nedelko, V., Hassa, T., Hamzei, F., Weiller, C., Binkofski, F., Schoenfeld, M. A., . . . Dettmers, C. (2010). Age-independent activation in areas of the mirror neuron system during action observation and action imagery. A fMRI study. *Restorative Neurology and Neuroscience, 28*(6), 737-747. doi: 10.3233/RNN-2010-0542

Nielsen, J. (1997). The use and misuse of focus groups. *Software, IEEE, 14*(1), 94-95. doi: 10.1109/52.566434

Nieuwboer, A., Rochester, L., Müncks, L., & Swinnen, S.P. (2009). Motor learning in Parkinson's disease: limitations and potential for rehabilitation. *Parkinsonism & Related Disorders, 15*, S53-S58. doi: 10.1136/jnnp.200X.097923

Norman, D. A. (2002). *The design of everyday things*. New York, NY: Basic Books.

Nouri, F., & Lincoln, N. (1987). An extended activities of daily living scale for stroke patients. *Clinical Rehabilitation, 1*(4), 301-305. doi: 10.1177/026921558700100409

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*(1), 97-113. doi: 10.1016/0028-3932(71)90067-4

Paccalin, C., & Jeannerod, M. (2000). Changes in breathing during observation of effortful actions. *Brain Research, 862*(1), 194-200. doi: 10.1016/S0006-8993(00)02145-4

Page, S. J., Levine, P., & Leonard, A. (2007). Mental practice in chronic stroke: results of a randomized, placebo-controlled trial. *Stroke, 38*(4), 1293-1297. doi: 10.1161/01.STR.0000260205.67348.2b

Pelosin, E., Avanzino, L., Bove, M., Stramesi, P., Nieuwboer, A., & Abbruzzese, G. (2010). Action observation improves freezing of gait in patients with Parkinson's disease. *Neurorehabilitation and Neural Repair, 24*(8), 746-752. doi: 10.1177/1545968310368685

Personnier, P., Kubicki, A., Laroche, D., & Papaxanthis, C. (2010). Temporal features of imagined locomotion in normal aging. *Neuroscience Letters, 476*(3), 146-149. doi: 10.1016/j.neulet.2010.04.017

Posner, M. I., & Raichle, M. E. (1994). *Images of mind*. New York, NY: Scientific American Library/Scientific American Books.

Prinz, W. (1987). *Ideo-motor action.* Hillsdale, NJ: Erlbaum.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9(*2), 129-154. doi: 10.1080/713752551

Put, K., Wagemans, J., Jaspers, A., & Helsen, W. F. (2013). Web-based training improves on-field offside decision-making performance. *Psychology of Sport and Exercise, 14*(4), 577-585. doi: 10.1016/j.psychsport.2013.03.005

Pylyshyn, Z. W. (1973). What the mind's eye tells the mind's brain: A critique of mental imagery. *Psychological Bulletin, 80*(1), 1-12. doi: 10.1080/713752551

Pylyshyn, Z. W. (2000). Situating vision in the world. *Trends in Cognitive Sciences, 4*(5), 197-207. doi: 10.1016/S1364-613(00)1477-7

Pylyshyn, Z. W. (2003). Return of the mental image: are there really pictures in the brain? *Trends in Cognitive Sciences, 7*(3), 113-118. doi: 10.1016/S1364-6613(03)00003-2

Ramachandran, V.A., & Altschuler, E.L. (2009). The use of visual feedback, in particular mirror visual feedback, in restoring brain function. *Brain, 132*(7), 1693-1710. doi: 10.1093/brain/awp135

Ramsey, R., Cumming, J., Eastough, D., & Edwards, M. G. (2010). Incongruent imagery interferes with action initiation. *Brain and Cognition, 74*(3), 249-254. doi: 10.1016/j.bandc.2010.08.005

Reinthal, A., SZirony, K., Clark, C., Swiers, J., Kellicker, M., & Linder, S. (2012). Engage: Guided activity-based gaming in neurorehabilitation after stroke: A pilot study. *Stroke Research and Treament, Article ID 784232*, 1-10. doi: 10.1155/2012/784232

Richardson, D. C., & Spivey, M. J. (2000). Representation, space and Hollywood squares: looking at things that aren't there anymore. *Cognition, 76*, 269-295. doi: 10.1016/S0010-0277(00)00084-6

Rizzolatti, G., & Arbib, M. A. (1998). Language within our grasp. *Trends in Neurosciences, 21*(5), 188-194. doi: 10.1016/S0166-2236(98)01260-0

Rizzolatti, G., Camarda, R., Fogassi, L., Gentilucci, M., Luppino, G., & Matelli, M. (1988). Functional organization of inferior area 6 in the macaque monkey. *Experimental Brain Research, 71*(3), 491-507. doi: 10.1007/BF00248742

Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature, 2*, 661-670.

Roberts, R., Callow, N., Hardy, L., Markland, d., & Bringer, J. (2008). Movement imagery ability: development and assessment of a revised version of the Vididness and Movement Imagery Questionnaire. *Journal of Sport & Exercise Psychology, 30*, 200-221.

Robertson, I. H., & Murre, J. M. U. (1999). Rehabiliation of brain damage: brain plasticity and pinciples of guided recovery. *Psychological Bulletin, 125*, 544-575.

Rodionov, V., Zislin, J., & Elidan, J. (2004). Imagination of body rotation can induce eye movements. *Acta Otolaryngologica, 124*(6), 684-689. doi: 10.1080/00016480410017017

Rönnlund, M., Nyberg, L., Bäckman, L., & Nilsson, L. (2005). Stability, growth, and decline in adult life span development of declarative memory: cross-sectional and longitudinal data from a population-based study. *Psychology and Aging, 20*(1), 3-18. doi: 10.1037/0882-7974.20.1.3

Roosink, M, & Zijdewind, I. (2010). Corticospinal excitability during observation and imagery of simple and complex hand tasks: Implications for motor rehabilitation. *Behavioural Brain Research, 213*, 35-41. doi: 10.1016/j.bbr.2010.04.027

Ruby, P., & Decety, J. (2001). Effect of subjective perspective taking during simulation of action: a PET investigation of agency. *Nature Neuroscience, 4*(5), 546-550.

Ryan, J. D., & Villate, C. (2009). Building visual representations: the binding of relative spatial relations across time. *Visual Cognition, 17*(1-2), 254-272. doi: 10.1080/13506280802336362

Rymal, A. M., & Ste-Marie, D. M. (2009). Does self-modeling affect imagery ability or vividness? *Journal of Imagery Research in Sport and Physical Activity, 4*(1), 1-14. doi: 10.2202/1932-0191.1035

Saimpont, A., Malouin, F., Tousignant, B., & Jackson, P. L. (2013). Motor imagery and aging. *Journal of Motor Behavior, 45*(1), 21-28. doi: 10.1080/00222895.2012.740098

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*, 403-428. doi: 10.1016/j.neurobiolaging.2008.09.023

Salthouse, T. A. (2009). When does age-related cognitive decline begin? *Neurobiology of Aging, 30*(4), 507-514. doi: 10.1016/j.neurobiolaging.2008.09.023

Salthouse, T. A., & Lichty, W. (1985). Tests of the neural noise hypothesis of age-related cognitive change. *Joural of Gerontology, 40*(4), 443-450. doi: 10.1093/geronj/40.4.443

Sartori, L., Betti, S., Perrone, C., & Castiello, U. (2014). Temporal coupling of congruent and non-congruent motor responses during action observation. Manuscript submitted for publication.

Sattler, J. M. (1970). Racial "experimenter effects" in experimentation, testing, interviewing, and psychotherapy. *Psychological Bulletin, 73*(2), 137. doi: 10.1037/h0028511

Schaal, S., Sternad, D., Osu, R., & Kawato, M. (2004). Rhythmic arm movement is not discrete. *Nature Neuroscience, 7,* 1137-1144. doi: 10.1038/mm1322

Schuster, C., Hilfiker, R., Amft, O., Scheidhauer, A., Andrews, B., Butler, J., . . . Ettlin, T. (2011). Best practice for motor imagery: a systematic literature review on motor imagery training elements in five different disciplines. *BMC medicine, 9*(1), 75. doi: 10.1186/1741-7015-9-75

Schutz-Bosbach, S., & Prinz, W. (2007). Perceptual resonance: action-induced modulation of perception. *Trends in Cognitive Sciences, 11*(8), 349-355. doi: 10.1016/j.tics.2007.06.005

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., . . . Lipps, D. B. (2010). Motor control and aging: links to age-related brain structural, functional, and biochemical effects. *Neuroscience & Biobehavioral Reviews, 34*(5), 721-733. doi: 10.1016/j.neubiorev.2009.10.005

Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on the useful field of view. *Experimental Aging Research, 26*, 103-120. 1 doi: 0.1080/036107300243588

Shapiro, K. L., & Raymond, J. E. (1989). Training of efficient oculomotor strategies enhances skill acquisition. *Acta Psychologica, 71*(1), 217-242. doi: 10.1016/0001-6918(89)90010-3

Shinoda, H., Hayhoe, M. M., & Shrivastava, A. (2001). What controls attention in natural environments? *Vision Research, 41*(25), 3535-3545. doi: 10.1016/S0042-6989(01)00199-7

Sirigu, A., & Duhamel, J. R. (2001). Motor and visual imagery as two complementary but neurally dissociable mental processes. *Journal of Cognitive Neuroscience, 13*, 910-919. doi: 10.1162/089892901753165827

Sirigu, A., Duhamel, J. R., Cohen, L., Pillon, B., Dubois, B., & Agid, Y. (1996). The mental representation of hand movements after parietal cortex damage. *Science, 273*, 1564-1568. doi: 10.1126/science.273.5281.1564

Skoura, X., Papaxanthis, C., Vinter, A., & Pozzo, T. (2005). Mentally represented motor actions in normal aging. I. Age effects on the temporal features of overt and covert execution of actions. *Behavioural Brain Research, 165*(2), 229-239. doi: 10.1016/j.bbr.2005.07.023

Skoura, X., Personnier, P., Vinter, A., Pozzo, T., & Papaxanthis, C. (2008). Decline in motor prediction in elderly subjects: right versus left arm differences in mentally simulated motor actions. *Cortex, 44*(9), 1271-1278. doi: 10.1016/j.cortex.2007.07.008

Smith, D. K., Collins, D. J., & Hale, B. (1998). Imagery perspectives and karate performance. *Journal of Sports Sciences, 16*, 103-104.

Smith, D. K., Wright, C. J., & Cantwell, C. (2008). Beating the bunker: the effect of PETTLEP imagery on golf bunker shot performance. *Research Quarterly for Exercise and Sport, 79*(3), 385-391.

Spivey, M. J., & Geng, J. J. (2001). Oculomotor mechanisms activated by imagery and memory: eye movements to absent objects. *Psychological Research, 65,* 235-241. doi: 10.1007/s004260100059

Stevens, J. A. (2005). Interference effects demonstrate distinct roles for visual and motor imagery during the mental representation of human action. *Cognition, 95*(3), 329-350. doi: 10.1016/j.cognition.2004.02.008

Thomas, D. R. (2003). A general inductive approach for qualitative data analysis. *American Journal of Evaluation, 27*(2). doi: 10.1177/1098214005283748

Thomas, N. J. T. (1999). Are theories of imagery theories of imagination?: An active perception approach to conscious mental content. *Cognitive Science, 23*(2), 207-245. doi: 10.1207/s15516709cog2302_3

Tokumaru, O., Mizumoto, C., Takada, Y., & Ashida, H. (2003). EEG activity of aviators during imagery flight training. *Clinical neurophysiology, 114*(10), 1926-1935. doi: 10.1016/S1388-2457(03)00172-X

Tupper, A, & Henley, S. (1987). Predictive factors in stroke outcome and implications for intervention. *International Journal of Rehabilitation Research, 10*, 119-121. doi: 10.1097/00004356-198712005-00024

Uithol, S., van Rooij, I., Bekkering, H., & Haselager, P. (2011). Understanding motor resonance. *Social Neuroscience, 6*(4), 388-397. doi: 10.1080/17470919.2011.559129

Underwood, G., Foulsham, T., & Humphrey, K. (2009). Saliency and scan patterns in the inspection of real-world scenes: Eye movements during encoding and recognition. *Visual Cognition, 17*(6-7), 812-834. doi: 10.1080/13506280902771278

Ungerleider, S., & Golding, J. M. (1991). Mental practice among olympic athletes. *Perceptual and Motor Skills, 72*(3), 1007-1017. doi: 10.2466/pms.1991.72.3.1007

Van Sonderen, J. F., & Denier Van der Gon, J. J. (1991). Reaction-time-dependent differences in the initial movement direction of fast goal-directed arm movements. *Human Movement Science, 10*(6), 713-726. doi: 10.1016/0167-9457(91)90024-R

Vargas, C. D., Olivier, E., Craighero, L., Fadiga, L., Duhamel, J. R., & Sirigu, A. (2004). The influence of hand posture on corticospinal excitability during motor imagery: a transcranial magnetic stimulation study. *Cerebral Cortex, 14*(11), 1200-1206. doi: 10.1093/cercor/bhh080

Vickers, J. N. (1996). Visual control when aiming at a far target. *Journal of Experimental Psychology: Human Perception and Performance, 22*(2), 342-354. doi: 10.1037/0096-1523.22.2.342

Vickers, J. N. (2007). *Perception, cognition, and decision training: The quiet eye in action*. US: Human Kinetics.

Vickers, J. N. (Ed.). (2009). Advances in coupling perception and action: the quiet eye as a bidirectional link between gaze, attention, and action. *Progress in Brain Research, 174*, 279-288. doi: 10.1016/S0079-6123(09)01322-3

Vine, S. J., Lee, D., Moore, L. J., & Wilson, M. R. (2013). Quiet eye and choking: online control breaks down at the point of performance failure. *Medicine & Science in Sports & Exercise, 45*(10), 1988-1994. doi: 10.1249/MSS.0b013e31829406c7

Viviani, P. (1990). Eye movements in visual search: Cognitive, perceptual, and motor control aspects. In E. Kowler (Ed.), *Eye movements and their role in* *visual and cognitive processes. Reviews of oculomotor research V4* (pp. 353–383). Amsterdam: Elsevier.

Vogt, S., Rienzo, F. D., Collet, C., Collins, A., & Guillot, A. (2013). Multiple roles of motor imagery during action observation. *Frontiers in Human Neuroscience, 7*(807), 1-13. doi: 10.3389/fnhum.2013.00807

Vogt, S., Taylor, P., & Hopkins, B. (2003). Visuomotor priming by pictures of hand postures: perspective matters. *Neuropsychologia, 41*(8), 941-951. doi: 10.1016/s0028-3932(02)00319-6

Vul, E., Harris, C., Winkielman, P., & Pashler, H. (2009). Puzzlingly high correlations in fMRI studies of emotion, personality, and social cognition. *Perspectives on Psychological Science, 4*(3), 274-290. doi: 10.1111/j.1745-6924.2009.01125.x

Wade, D. T., & Hewer, R. L. (1987). Functional abilities after stroke: measurement, natural history and prognosis. *Journal of Neurology, Neurosurgery & Psychiatry, 50*(2), 177-182. doi: 10.1136/jnnp.50.2.177

Wakefield, C., Smith, D., Moran, A. P., & Holmes, P. S. (2013). Functional equivalence or behavioural matching? A critical reflection on 15 years of research using the PETTLEP model of motor imagery. *International Review of Sport and Exercise Psychology, 6*, 105-121. doi: 10.1080/1750984x.2012.724437

Webb, A., Knott, A., & Macaskill, M. R. (2010). Eye movements during transitive action observation have sequential structure. *Acta Psychologica, 133*(1), 51-56. doi: 10.1016/j.actpsy.2009.09.001

White, A., & Hardy, L. (1995). Use of different imagery perspectives on the learning and performance of different motor skills. *British Journal of Psychology, 86*(2), 169-180. doi: 10.1111/j.2044-8295.1995.tb02554.x

Williams, A. M., & Grant, A. (1999). Training perceptual skill in sport. *International Journal of Sport Psychology*, 30(2), 194-220.

Williams, A. M., Singer, R. N., & Frehlich, S. G. (2002). Quiet eye duration, expertise, and task complexity in near and far aiming tasks. *Journal of Motor Behavior, 34*(2), 197-207. doi: 10.1080/00222890209601941

Williams, A. M., Ward, P., & Chapman, C. (2003). Training perceptual skill in field hockey: Is there transfer from the laboratory to the field? *Research Quarterly for Exercise and Sport, 74*(1), 98-103. doi: 10.1080/02701367.2003.10609068

Williams, S. E., Cooley, S. J., & Cumming, J. (2013). Layered stimulus response training improves motor imagery ability and movement execution. *Journal of Sport & Exercise Psychology*, 35, 60-71. doi:

Wilson, C. Smith, D. Stockley, R. & Holmes, P. S. (2012) *Do physiotherapists and occupational therapists use cognitive therapies during stroke rehabilitation?* Paper presented at the 7th Annual Research, Imagery and Observation Conference, Liverpool, UK.

Woodworth, R. S. (1899). Accuracy of voluntary movement. *Psychological Monograph Supplements, 3*(2 whole No. 13).

Zelinsky, G. J. (2013). Understanding scene understanding. *Frontiers in Psychology, 4*(954), 1-4. doi: 10.3389/fpsyg.2013.00954

Zhao, M., & Bülthoff, I. (2013). The other-race effect in face recognition is sensitive to face format at encoding. *Visual Cognition, 21*(6), 722-725. doi: 10.1080/13506285.2013.844971

9 Appendices

Appendix A: The Edinburgh Handedness Inventory (Oldfield, 1971)

Edinburgh Handedness Inventory – Oldfield (1971)

Name: Date:

Please indicate your preference in the use of hands in the following activities by putting a + in the appropriate column. Where your preference is so strong that you would never try to use the other hand unless absolutely forced to, put ++. If you are really indifferent put a + in both columns.

Some of the activities require both hands. In these cases, the part of the task, or object, for which hand preference is wanted is indicated in parentheses.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Right	Left
Writing		
Drawing		
Throwing		
Scissors		
Comb		
Toothbrush		
Knife (without fork)		
Spoon		
Hammer		
Screwdriver		
Tennis racquet		
Knife (with fork)		
Cricket bat (lower hand)		
Golf club (lower hand)		
Broom (upper hand)		
Striking match (match hand)		
Opening box/jar (lid hand)		
Dealing cards (card dealing hand)		
Which foot do you prefer to kick with?		
Which eye do you use when using only one?		

Appendix B: The Movement Imagery Questionnaire – Revised Second Version (Gregg et al., 2010)

MIQ – RS

Name:

This questionnaire concerns two ways of mentally performing movements that are used by some people more than by others, and are more applicable to some types of movements than others. The first is attempting to form a visual image or picture of a movement in your mind. The second is attempting to feel what performing a movement is like without actually doing the movement. You are requested to do both of these mental tasks for a variety of movements in this questionnaire, and then rate how easy/difficult you found the tasks to be. The ratings that you give are not designed to assess how "good" or "bad" you are at performing these mental tasks. They are attempts to discover the capacity individuals show for performing these tasks for different movements. There are no right or wrong ratings or some ratings that are better than others.

Each of the following statements describes a particular action or movement. Read each statement carefully and then actually perform the movement as described. Only perform the movement a single time. Return to the starting position for the movement just as if you were going to perform the action a second time. Then, depending on which of the following you are asked to do, either (1) form as clear and vivid a visual image as possible of the movement just performed, or (2) attempt to feel yourself making the movement just performed without actually doing it.

After you have completed the mental task required, rate the ease/difficulty with which you were able to do the task. Take your rating from the following scales.

RATING SCALES:

Visual Imagery Scale

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

Kinesthetic (feeling) Imagery Scale

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

Be as accurate as possible and take as long as you feel necessary to arrive at the proper rating for each movement. You may choose the same rating for any number of movements "seen" or "felt" and it is not necessary to utilize the entire length of the scale.

***1. STARTING POSITION*:** Stand with your feet and legs together and your arms at your sides.

***ACTION*:** Raise your one knee as high as possible so that you are standing on one leg with your other leg flexed (bent) at the knee. Now lower your leg so that you are again standing on two feet.

***MENTAL TASK*:** Assume the starting position. Attempt to feel yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

***RATING*:** _____________

***2. STARTING POSITION*:** While sitting, put your hand on your lap and make a fist.

***ACTION*:** Raise your hand above your head until your arm is fully extended, keeping your fingers in a fist. Next, lower your hand back to your lap while maintaining a fist.

***MENTAL TASK*:** Assume the starting position. Attempt to see yourself making the movement just performed with as clear and vivid a visual image as possible. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

***RATING*:** _____________

3. STARTING POSITION: Extend your arm straight out to your side so that it is parallel to the ground, with your fingers extended and your palm down.

ACTION: Move your arm forward until it is directly in front of your body (still parallel to the ground). Keep your arm extended during the movement and make the movement slowly. Now move your arm back to the starting position, straight out to your side.

MENTAL TASK: Assume the starting position. Attempt to feel yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

RATING: _____________

4. STARTING POSITION: Stand with your arms fully extended above your head.

ACTION: Slowly bend forward at the waist and try and touch your toes with your fingertips. Now return to the starting position, standing erect with your arms extended above your head.

MENTAL TASK: Assume the starting position. Attempt to see yourself making the movement just performed with as clear and vivid a visual image as possible. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

RATING: _____________

5. STARTING POSITION: Put your hand in front of you about shoulder height as if you are about to push open a swinging door. Your fingers should be pointing upwards.

ACTION: Extend your arm fully as if you are pushing open the door, keeping your fingers pointing upwards. Now let the swinging door close by returning your hand and arm to the starting position.

MENTAL TASK: Assume the starting position. Attempt to see yourself making the movement just performed with as clear and vivid a visual image as possible. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

RATING: _____________

6. STARTING POSITION: While sitting, put your hand in your lap. Pretend you see a drinking glass on a table directly in front of you.

ACTION: Reach forward, grasp the glass and lift it slightly off the table. Now place it back on the table and return your hand to your lap.

MENTAL TASK: Assume the starting position. Attempt to feel yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

RATING: _____________

***7. STARTING POSITION*:** Your hand is at your side. Pretend there is a door in front of you that is closed.

***ACTION*:** Reach forward, grasp the door handle and pull open the door. Now gently shut the door, let go of the door handle and return your arm to your side.

***MENTAL TASK*:** Assume the starting position. Attempt to feel yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

***RATING*:** _____________

8. STARTING POSITION: Stand with your feet and legs together and your arms at your sides.

***ACTION*:** Raise your one knee as high as possible so that you are standing on one leg with your other leg flexed (bent) at the knee. Now lower your leg so that you are again standing on two feet.

***MENTAL TASK*:** Assume the starting position. Attempt to see yourself making the movement just performed with as clear and vivid a visual image as possible. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

***RATING*:** _____________

***9. STARTING POSITION*:** While sitting, put your hand on your lap and make a fist.

***ACTION*:** Raise your hand above your head until your arm is fully extended, keeping your fingers in a fist. Next, lower your hand back to your lap while maintaining a fist.

***MENTAL TASK*:** Assume the starting position. Attempt to feel yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

***RATING*:** _____________

***10. STARTING POSITION*:** Extend your arm straight out to your side so that it is parallel to the ground, with your fingers extended and your palm down.

***ACTION*:** Move your arm forward until it is directly in front of your body (still parallel to the ground). Keep your arm extended during the movement and make the movement slowly. Now move your arm back to the starting position, straight out to your side.

***MENTAL TASK*:** Assume the starting position. Attempt to see yourself making the movement just performed with as clear and vivid a visual image as possible. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

***RATING*:** _____________

***11. STARTING POSITION*:** Stand with your arms fully extended above your head.

***ACTION*:** Slowly bend forward at the waist and try and touch your toes with your fingertips. Now return to the starting position, standing erect with your arms extended above your head.

***MENTAL TASK*:** Assume the starting position. Attempt to feel yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

***RATING*:** _____________

***12. STARTING POSITION*:** Put your hand in front of you about shoulder height as if you are about to push open a swinging door. Your fingers should be pointing upwards.

***ACTION*:** Extend your arm fully as if you are pushing open the door, keeping your fingers pointing upwards. Now let the swinging door close by returning your hand and arm to the starting position.

***MENTAL TASK*:** Assume the starting position. Attempt to feel yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

***RATING*:** _____________

***13. STARTING POSITION*:** While sitting, put your hand in your lap. Pretend you see a drinking glass on a table directly in front of you.

***ACTION*:** Reach forward, grasp the glass and lift it slightly off the table. Now place it back on the table and return your hand to your lap.

***MENTAL TASK*:** Assume the starting position. Attempt to see yourself making the movement just performed with as clear and vivid a visual image as possible. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

***RATING*:** _____________

***14. STARTING POSITION*:** Your hand is at your side. Pretend there is a door in front of you that is closed.

***ACTION*:** Reach forward, grasp the door handle and pull open the door. Now gently shut the door, let go of the door handle and return your arm to your side.

***MENTAL TASK*:** Assume the starting position. Attempt to see yourself making the movement just performed with as clear and vivid a visual image as possible. Now rate the ease/difficulty with which you were able to do this mental task.

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

***RATING*:** _____________

Appendix C: The Vividness of Movement Imagery Questionnaire-2 (Roberts et al., 2008)

Vividness of Movement Imagery Questionnaire-2

Movement imagery refers to the ability to imagine a movement. The aim of this questionnaire is to determine the vividness of your movement imagery. The items of the questionnaire are designed to bring certain images to your mind. You are asked to rate the vividness of each item by reference to the 5-point scale. After each item, circle the appropriate number in the boxes provided. The first column is for an image obtained watching yourself performing the movement from an external point of view (External Visual Imagery), and the second column is for an image obtained from an internal point of view, as if you were looking out through your own eyes whilst performing the movement (Internal Visual Imagery). The third column is for an image obtained by feeling yourself do the movement (Kinaesthetic imagery). Try to do each item separately, independently of how you may have done other items. Complete all items from an external visual perspective and then return to the beginning of the questionnaire and complete all of the items from an internal visual perspective, and finally return to the beginning of the questionnaire and complete the items while feeling the movement. The three ratings for a given item may not in all cases be the same. For all items please have your eyes CLOSED.

Think of each of the following acts that appear on the next page, and classify the images according to the degree of clearness and vividness as shown on the RATING SCALE.

RATING SCALE. The image aroused by each item might be:

Perfectly clear and as vivid (as normal vision or feel of movement)	……………	RATING 1
Clear and reasonably vivid	……………	RATING 2
Moderately clear and vivid	……………	RATING 3
Vague and dim	……………	RATING 4
No image at all, you only "know" that you are thinking of the skill.	……………	RATING 5

	Watching yourself performing the movement (External Visual Imagery)						Looking through your own eyes whilst performing the movement (Internal Visual Imagery)						Feeling yourself do the movement (Kinaesthetic Imagery)				
Item	Perfectly clear and vivid as normal vision	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	No image at all, you only know that you are thinking of the skill		Perfectly clear and vivid as normal vision	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	No image at all, you only know that you are thinking of the skill		Perfectly clear and vivid as normal feel of movement	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	No image at all, you only know that you are thinking of the skill
1.Walking	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
2.Running	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
3.Kicking a stone	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
4.Bending to pick up a coin	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
5.Running up stairs	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
6.Jumping sideways	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
7.Throwing a stone into water	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
8.Kicking a ball in the air	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
9.Running downhill	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
10.Riding a bike	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
11.Swinging on a rope	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
12.Jumping off a high wall	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5

Appendix D: In house questionnaire for measuring imagery performance during the VFT

In- house questionnaire

Name:

1. Using the scales below, please rate the ease/difficultly with which you were able to perform the imagery and observation reach and point task. The ratings that you give are not designed to assess how "good" or "bad" you are at performing these mental tasks. There are no right or wrong ratings or some ratings that are better than others.

RATING SCALES:

Visual Imagery Scale

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy not hard)	Somewhat easy to see	Easy to see	Very easy to see

Kinesthetic (feeling) Imagery Scale

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy not hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

	Visual Rating	Kinaesthetic Rating
Imagery		
Observation		

2. Please circle the mental task that you preferred using: **Imagery** **Observation**