VISUAL CONTROL OF BIMANUAL MOVEMENTS

By

SHILOKH DAVID SARDAR

A thesis submitted to the

University of Birmingham

for the degree of

DOCTOR OF PHILOSOPHY

School of Sport, Exercise and Rehabilitation Sciences

College of Life and Environmental Sciences

University of Birmingham

July 2020

Thesis summary

Goal directed reaching forms an integral part of human routine movements, and we have a remarkable faculty to perform such actions with both upper limbs and coordinating these to achieve individual and collective outcomes. Everyday actions such as eating using a knife and fork, tying shoelaces, typing on a keyboard distort the complexity involved in the nature of timing synchrony and coordination that occurs between the two limbs. Several factors that can affect the synchrony between limbs during concurrent bimanual movements are; task difficulty, required movement symmetry, competition between limbs for visual resources, hand dominance and impairment to motor or visual system. This thesis explores these factors through a series of experiments in both young and older unimpaired individuals as well as those with limb impairment as a result of stroke.

Although observations in relation to movement of the upper limbs and their coordination have been recorded throughout written history, it is during the last few decades where the majority of related empirical research has been undertaken. How the brain controls and coordinates movement remains an important yet inconclusive area in motor control literature thus far, however, it grows as a topic of research due to more advanced technological capabilities and implications for upper limb movement disorder rehabilitation. Studies of the upper limb have considered the spatial and temporal properties of unimanual and bimanual movements; exploring the interaction between the two limbs during bimanual movements. In movements to two separate targets, movement time symmetry (temporal symmetry) has been observed between the two limbs, where

the movements are initiated and terminated in similar timing. However, as the relative precision requirements and thus difficulty of the required movement to two separate targets increases, inter-limb coordination may be disrupted. To date, motor control research has failed to establish specific factors that are involved in the integration of the two limbs for bimanual coordination. As well as addressing the interaction between the two limbs, this thesis explores the contribution made by overt and covert visual attention to the control of visual guided upper limb movements with a focus on the coordination between the two limbs. It also explores related performance in stroke survivors with hemiparesis along with an older adults control group; in doing so, this research in the first to explore the important function of visually-guided bimanual movements while examining both eye and limb movements in a clinical population.

This thesis is organised into three individual yet interconnected experimental chapters. Following introduction of the key themes motivating the research and related relevant literature (Chapter 1), a general methods section (Chapter 2) describes the development and details of the underlying experimental paradigm and protocol used in all the experimental chapters. Modifications to this basic approach are detailed in the methods sections of individual experimental chapters. Next, the experimental chapters are presented (Chapter 3, 4 and 5). Experiment 1 examines visual control and coordination of the limbs during unimanual and bimanual reaching movements in young left and right-handed adults (Chapter 3). Next, the experimental protocol was changed to restrict the visual control of upper limb movements and the motor coordination between the two limbs was studied (Chapter 4). Unimanual and bimanual movements were examined while participants maintained visual fixation (i.e. without eye movements), and any *errant saccades* were monitored in addition to the measures gathered in Chapter 3. The third experiment (Chapter 5) examined unimanual and bimanual control and coordination in participants following hemiparetic stroke and compared their performance with a group of age-matched control participants. A general discussion with conclusions and future directions is presented in Chapter 6.

Acknowledgements

First and foremost, I express my greatest gratitude to my supervisor ‘Professor’ Dr David Punt. The PhD journey has been at times tough to follow, and I would not have been able to complete without his guidance, encouragement and support. His patience with me has been immense in the last 5 years, and he has been incredibly positive and inspired me to trust the process and be confident in my own work. It has been a great pleasure and honour working with Dr Punt; I look forward to continue adding ‘Pint with Punt’ in my calendar.

Next, I thank my second supervisor Dr Sang-Hoon Yeo, and Dr Jon Allsop for their technical support and contribution, the programming input was instrumental in the task set up and analytical work.

Next and related to the academic field I am grateful for and to Sarah Voets (SHEM); my closest friend whom I am glad to have shared the journey with; she was and remains a constant source of support, motivation, joy, and coffee. I also thank Stuart Mackenzie, whose support and practical help was invaluable to me. I am indebted to my friends and colleagues along with the rest of the Sportex graduate community have all contributed, whether knowingly or not by encouragement and practical assistance.

I express my gratitude to my ‘former housemates’ Soli, Anna, Shallum, and Grace for their support and encouragement, which sustained me on a day-to-day basis and allowed me to

keep moving forward. A special thanks to my friend (and niece) Grace Phoebe for teaching me how to live in the moment and focus on what is important in life.

I thank my parents David & Nasreen, who inspire me in all walks of life. Their boundless optimism and belief in me, their endless love for me, and the never-ending support and encouragement inspire me to dream and live big.

The last and most important person that I would like to thank is my wife Sharon. Her motivational talks, patience, love and sustenance has been immeasurably helpful to me inside and outside of my academic journey. Through this PhD journey she has sacrificed most for ‘the science’, for which I and the thesis are most grateful.

Contents listings

List of Figures

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

List of tables

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

Chapter 1: General introduction

Background

The history of evolution indicates that before language and abstract learning, the defining feature that separated us from our evolutionary ancestors is the way in which we move. In evolving to bipedalism, which became a defining characteristic of our ancestors for over 2.5 million years (Bradshaw and Rogers, 1993), our species moved away from using the upper limbs for balance and locomotion; instead using upper limbs as a means by which to interact with and manipulate the surrounding environment. The human brain evolved to specialise neural processing for a variety of upper limb actions, ranging from reaching and grasping to coordinating limbs in order to manipulate objects to use as tools. How the central nervous system (CNS) generates and controls movement has been an area of interest for philosophers and scientists for centuries.

Early limb control literature on limb movements and coordination dates back to the 19th century, where Woodworth (1899) designed an experiment to study upper limb aiming movements using a pencil stylus on paper attached to a rotating drum. Woodworth (1899) described the limb movements as having two phases; a ballistic movement phase at the start of movement followed by a corrective movement phase towards the end of the movement. A noteworthy finding was the increasing movement error as the speed of movement increased; Figure 1.1 shows the relationship between movement accuracy and number of movements per minute (speed) for the left and right limbs.

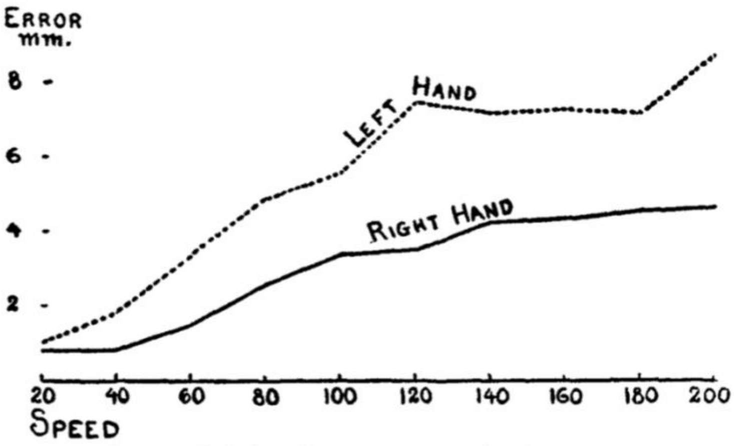


FIG. 5. Relation of accuracy to speed. Eyes open.

Figure 1.1 Illustration showing accuracy of the left and right hand.
NB. Speed was calculated as number of movements per minute (Woodworth, 1899)

More recently, this two-stage model has been updated to include the idea that kinaesthetic and visual information is gathered and processed throughout the movement, termed 'online' corrections (Diedrichsen et al., 2004).

Considering Woodworth's (1899) experiment, in order to produce seemingly simple unimanual and bimanual movements such as pointing to an object in close proximity, interaction between the nervous and musculoskeletal system is required to coordinate the shoulder, elbow and wrist joints along with analogous muscles (Liu et al., 2013). Neural processing comprises of a necessary movement plan followed by motor commands to execute the actions, otherwise known as a motor programme (Schmidt, 1975). The movement plan may require updating 'online' through sensory proprioceptive or visual input as the movement progresses, providing feedback on the error in the upper limb's desired versus actual position, and in turn allowing accurate goal direction of movement (Desmurget et al., 1998).

Woodsworth's (1899) observations on increased time and reduced accuracy and the input of visual control suggest a temporal or spatial cost to making task constrained, goal directed movements. Each movement can be executed in several different ways, as the limb is free to move in a three-dimensional space and devoid of time constraints. However, an evolutionary progression viewpoint would suggest that not only does the motor system compute the planning, execution and control of such movements, it does so in the most time and energy efficient manner (Bernstein, 1967). To reduce the time and energy cost of upper limb movements, the visuomotor system strives to reduce the degrees of freedom in each movement. Bernstein (1967) defined limb coordination as "the process of mastering redundant degrees of freedom of the moving organ"; in other words, the visuomotor system's objective is to expend minimal musculoskeletal, visual and proprioceptive resources to complete limb movements with sufficient spatial and temporal accuracy.

For reaching and aiming movements, the motor system is presented with a speed and accuracy trade-off where, as first formally observed by Woodworth (1899), as the speed of the movements increases, their accuracy tends to decrease. Fitts (1954) developed the field further by introducing an important equation which quantifies the relationship between two further factors that determine the speed and accuracy of aiming movements; the task aiming difficulty defined by required precision and the time required to complete the movement.

The equation is as follows; $MT = a + b \log(2A/W)$, where MT denotes the movement time, A denotes the amplitude or distance of movement, W denotes the width of the target, and a and b are empirical constants. The term log (2A/W) is called the index of difficulty (ID) and equation implies that MT increases linearly with ID. This seemingly simple relationship between the time taken to complete movement and its difficulty belies the complexity involved in optimising motor and sensory organs to ensure adequate performance. Following on from Fitts' work in the 50s, there has been constant research in the field of upper limb reaching movements. However, given the prevalence and ecological proximity to daily life movements, bimanual movements have had comparatively less interest than unimanual movements in literature. The next section offers a brief overview on the methods used for upper limb research, followed by a short review of relevant literature on the control and coordination of reaching movements.

Research methods to study control and coordination of upper limbs

As with a majority of behavioural neuroscience and psychological sciences, understanding of any topic is largely dependent on the latest available technology. Early approaches to understanding brain function in human behaviour were post-mortems to correlate damaged areas to observed behaviour (Finger, 2004). Next, as the technology of the time allowed, Woodworth (1899), using a roll drum covered with paper, designed an experiment which required moving a stylus back and forth through a slit to two marked locations to gain insights into upper limb behaviour. Published nearly half a century later, research by Fitts (1954) is of pronounced importance for upper limb movement research; Fitts (1954) proposed a relationship between relative movement difficulty and the time it would take to complete movement (see above) by recording stylus movement to targets on a desktop. Movement time analysis by Fitts (1954) allowed researchers to gain an appreciation of temporal movement parameters being affected by target difficulty; however, a more refined view into the processes governing limb control is available by studying the kinematics of movement, from movement onset to movement end.

Methods to study temporal coordination between limbs, as observed in a kinetic task by Kelso et al. (1979) included rhythmic tapping tasks, where timing patterns of the separate limbs can be observed. Other methods include measuring temporal aspects of mirror-symmetrical (in-phase) movements, where homologous muscles are active simultaneously, and comparison with the anti-parallel (out-of-phase) mode, where homologous muscles are engaged in an alternating fashion; (Swinnen, 2002, Carson and Swinnen, 2002). Although beyond the scope of this thesis, neuroimaging presents capability and techniques to examine the human brain and infer evidence in motion perception and limb coordination using anatomical correlates. Other methods include the use of kinematics, for example studying the coordination between the limbs using circle drawing tasks (for example; Franz et al. (1991)), and tasks requirements which involve a combination of drawing circles with other discontinuous shapes (for example; Franz and Johnston-Frey (2003)). Whilst such methodology is useful in the spatial directional domain, it does not lend itself well to study of kinematic and temporal study of limb movements.

In motor control, motion capture has enhanced researchers' ability to measure kinematics of movement and is now the widely used tool for quantifying upper limb function (Nowak, 2008), and has applications in professional sports (Pueo and Jimenez-Olmedo, 2017) and clinical treatment of upper limb impairment (Wu et al., 2007). History of motion capture dates back to early 19th century, where Eadweard Muybridge, in 1887 placed a series of cameras in a row to capture the motion of a horse whist it trotted (Wing and Beek, 2004). Following the advancement of photography and capability of video recordings, motion capture was enhanced as video stills could be studied digitally. Markers placed on different body landmarks could be monitored at each frame, thereby allowing movements to be quantified with the data marker coordinates displacement over time. In motor control, particularly in prehension and reaching movements, Jeannerod (1981) was one of the first to employ motion capture to capture the differentiation between the different phases involved in a prehension movement; the transport phase (hand movement towards target) and the prehension (grasping) phase (Jeannerod, 1984), paving the way for further research as motion capture offered a robust design and an accurate measure of quantifying upper limb human movement; as well as showing similarity to Woodworth's suggestion that a movement consists of a ballistic movement followed by corrective movement. As technological advances in the field have allowed, the 21st century has seen an expansion in the use of robot-mediated tasks to measure upper limb behaviour (Duret et al., 2019).

Present day motion capture entails electronic systems with multiple cameras that are capable of capturing and generating three-dimensional data for each marker on body landmark at a timed frequency, which provides an accurate temporal and spatial representation of limb movement control and coordination. Chapter 2 discusses the use of motion capture in this thesis along with combination of methods for study of coordination of limbs as unimpaired and impaired participants make unimanual and bimanual reaching movements.

Brief review of relevant literature

Control and coordination of unimanual and bimanual reaching movements

A relatively modern area of motor control research, bimanual reaching has received little yet constant attention in academic research in the last few decades. Wiesendanger et al. (1996) states that limb movements and coordination between the limbs are adapted according to task requirements, with coordination constrained by the environment. In activities of daily life and in research task settings, upper limb movements can be categorised into three separate categories:

1. Unimanual movements – where one arm makes a movement; for example, switching a light switch on or off.
2. Symmetrical bimanual movement – where both arms move together in mirrored fashion, in temporal synchrony with similar contribution from each arm; for example, lifting an object with both hands.
3. Asymmetrical bimanual movements – where both hands are involved in a non-mirrored fashion; for example, holding an apple with one hand and cutting it with the other.

Pioneering research by Kelso et al. (1979) over forty years ago established that during reaching towards target pairs, the hands are in temporal synchrony with each other, starting and ending the movement at the same time although task instructions did not explicitly demand this. For unimanual movements, Fitts' Law (1954), which postulates that movement time increases as index of difficulty increases, was supported. However, for bimanual movements, in particular movements to which required unequal distance movement from each limb, the principle is seemingly defied, as temporal coupling is maintained even though each limb is tasked with a movement that has a very different index of difficulty, with similar findings observed in a separate experiment where participants were allowed unconstrained vision. In a follow-up study, Kelso et al. (1983) replicated the previous study in the first experiment, with changed task parameters for the second experiment, so that the required bimanual limb movements had an obstacle in the spatial path on one side between the start and end point. The third experiment required limb movements across the sagittal centre space, where participants reached to one side of space with both limbs. Despite differences in required movement pathway, direction for each limb and movement symmetry, temporal coupling between the limbs was observed in all three experiments. Findings from Jeannerod (1984) in a reach to grasp task reported similar findings; both limbs were closely synchronised and the timing of velocities and grip aperture were in temporal synchrony for both limbs. Findings from Corcos (1984) also showed temporal synchrony during asymmetrical bimanual movements, despite one experimental condition (condition D) requiring one limb to move twice the distance of the other limb. Findings suggest that temporal coupling during bimanual reaching movements may be the default strategy of movement for the visuomotor system, which Kelso et al.

(1979) proposed was the result of a synergetic, single motor command mechanism for upper limb bimanual movements. Theoretically, the above findings appear to suggest that the motor system coordinates bimanual movements in a synergistic manner to reduce the movement processing cost and therefore the degrees of freedom that require processing control (Bernstein, 1967).

Of particular relevance to this thesis and the overarching theme in the aforementioned studies is a key characteristic of bimanual movements; that participants tend to couple their limbs to a large extent although they are not instructed to do so (Swinnen, 2002, Franz and Johnston-Frey, 2003). On the contrary, some research suggests that limbs are not temporally coupled during bimanual movements. (Boessenkool et al., 1999), in bimanual pointing task, found that although average movement times showed synchrony between the limbs, when explored on a trial-by-trial basis the limbs were not in temporal synchrony after movement onset. Such findings highlight that although limbs may exhibit coupling at a ‘macro’ level, when considered closely small but reliable asynchronies may emerge. Jackson et al. (1999) conducted an experiment where participants made prehension movements to identical objects located at either the same distance (congruent) or different distances (incongruent) from the start position, and found that although limbs were synchronised at movement initiation, asynchronies between the limbs emerged as the movement unfolded, with limbs independently scaled respective to the size and distance from the target. Findings of asynchrony are replicated in Bingham et al. (2008) prehension study, where objects of different sizes, with different distances apart from each limb were used; asynchrony towards the end of movement was attributed to competing demands of each limb during unimanual and bimanual movements. Further support comes from Balakrishnan and Hinckley (2000) who observed that even when task demands for each limb are similar during bimanual movements (mirrored movements), the limbs were not always temporally synchronous.

Factors such as limb dominance (Kelso et al., 1983), task demands (Jackson et al., 1999) and attentional components (Balakrishnan and Hinckley, 2000, Bingham et al., 2008) influence how closely the two limbs are coupled temporally throughout bimanual movements. However, the aforementioned studies do not formally account for the role of visual feedback during bimanual movements, as during bimanual movements only one target can be foveated on at a given time, which creates competition between the limbs for the shared resource of vision, which consequently can result in asynchrony between the limbs. The following section addresses studies that have studied the role of vision in reaching movements, and how it interacts with temporal coupling between the limbs during bimanual reaching movements, as developing a better understanding of these issues is an objective of this thesis.

Role of vision in reaching movements

Temporal aspects of bimanual movements are affected by the sensory information available to the visuomotor system during movement (Diedrichsen et al., 2004). The coordination between eye and limb movements in natural tasks was studied by Land and Hayhoe (2001), with findings showing that manual manipulation of target objects was preceded by eye movements towards it. In reaching movements, the key function of eye movements is to enable the visuomotor system to formulate a movement plan for the limbs (Johansson et al., 2001). For bimanual movements, where vision cannot be directed to both targets at the same time, task demands may require adjustment or adaptation of the hand's movement strategies.

Fowler et al. (1991) found that during bimanual movements, the side of target with the higher index of difficulty showed longer movement times so that the limbs were asynchronous at movement end and attributed this asynchrony to the role of vision in guiding the limbs to their targets during bimanual movement, as only one target / limb side can be foveated at a given time. Similar findings are reported by Riek et al. (2003), who found synchrony between the limbs decreases that as movement unfolds, however, at movement end the limbs appear to be in synchrony. The deceleration 'hover' phase was highlighted as the phase during which movements are temporally uncoupled, as the visuomotor system visually guides each limb to its respective target; this is completed in a serial manner, where one limb hovers over its target whilst the other is being visually guided towards its respective target; however, movement end is marked when both the targets are touched in temporal synchrony. As the difference in movement difficulty for each limb increased (in asymmetrical conditions), the length of hover phase also increased, suggesting that the constraints of visual demands of a reaching task modulate its kinematics. Also reported by Srinivasan and Martin (2010), the 'hover phase' occurs during the deceleration part of the reaching movement, further empirical support for visual requirement constraints leading to asynchrony come from a study by Bruyn and Mason

(2009) who conducted a prehension task in young adults and found that although movement initiation time was similar for both conditions, vision constrained by the requirement to visually guide each limb onto its target towards the latter part of movement was a factor in causing asynchronies in total movement time.

Bruyn and Mason (2009) concluded that that visual requirements are not the only factor in modulating limb asynchrony, other factors include; biases in proprioceptive control of one limb (Goble and Brown, 2008b), attentional asymmetry between limbs (Buckingham and Carey, 2009), and asymmetrical reliance of limbs on visual feedback (Honda, 1982). Miller and Smyth (2012) studied the role of vision in bimanual coordination in discrete bimanual aiming movements. Findings showed greater synchrony in experiments in the absence of vison, as visual saccades are made after peak velocity (in the deceleration phase) for accurate acquisition of targets. In symmetrical and asymmetrical movements, the visuomotor system drives for synchronous movement, but is constrained by task demands. Task demands were deemed to be different for both limbs, where one may assume that the movement requirement difficulty for the non-dominant limb is higher than for the dominant limb.

Srinivasan and Martin (2010) reported that in instances where subjects are unable to foveate on two separate targets during reaching movements, the two limbs are decoupled temporally, resulting in four distinct movement strategies being observed; these are listed below:

“1. Terminal gaze strategy: Gaze is directed toward one of the targets (target 1) first and after completion of placement of the corresponding object, moves to the other target (target 2).

2. Predictive gaze strategy: Gaze is directed toward target 1 initially, but then redirected to target 2 even before the completion of placement at target 1.

3. Intermittent gaze strategy: Gaze is repeatedly switched from one target to another (more than once) during the execution of the bimanual task.

4. Selective gaze strategy: Gaze is directed at one of the targets and remains there until the completion of the entire bimanual task when both hands complete their placements.”

Research by Srinivasan and Martin (2010) and Miller and Smyth (2012) concludes that the visual demands of a task appear to be able to elicit asynchrony between the limbs; however the more precise relations between visual requirements of bimanual movements and task demands are less clear.

Although the role of vision control of bimanual movements has been addressed in literature, at the time of writing, there are no published studies that explore *how* vision/ eye movements are organised in control and coordination of the upper limbs during unimanual and bimanual reaching movements. This is of much interest and relevance to the thesis, as one of the aims and objectives is to determine the relations between vision and bimanual coordination in reaching movements.

Reaching movements in older adults population and stroke survivors

A key aim of the thesis was to examine the visual control of bimanual movements in hemiparetic stroke survivors. In preparation for this, here, previous literature is presented along with theoretical concepts.

As limb movement is innate and enhanced during childhood, the apparent simplicity of limb movements and the coordination between the two limbs whilst performing bimanual movements in daily life belie the skill and sophistication of the visuomotor system in their control and coordination. However, our reliance on the coordination becomes apparent during deterioration due to ageing or dysfunction due to impairment, such as hemiparesis following stroke. Given its importance in everyday function, the topic of bimanual limb coordination has received comparatively little attention in research. Furthermore, a majority of studies that have been conducted in the research field have used young participants; although older adults and stroke survivors are the groups that are predominantly affected by movement disorders.

Newell et al. (2006) highlight three distinct areas in which motor control is affected in ageing: (i) physical fitness aspects; (ii) the information processing activities that relate to variables such as reaction time and movement time and (iii) control of posture and locomotion and fine motor control of hand and finger force. The decline in bimanual control and coordination with ageing is reported in early work by Stelmach et al. (1988); who found longer movement times in unimanual and bimanual aiming movements compared to young participants. Furthermore, during bimanual movements, temporal asynchrony between the limbs at movement onset and movement end was greater for the older adults compared to young adults, suggesting that a decline in motor control was associated with ageing.

Coats and Wann (2012) compared young controls and older adults in a symmetrical and asymmetrical bimanual prehension task and reported no differences in overall movement time or deceleration between the two groups, as well as comparable performance on asymmetric bimanual movements. However, during bimanual movements, the older adults tended to spend a longer proportion of the reach movement in the final adjustment phase, suggesting that ageing may have an influence on the way in which feedback is utilised. The findings suggest that online control of the limbs was affected as participants were unable to foveate on both limbs during bimanual movements; and therefore required a longer time period to make limb adjustments at movement end. In the absence of visual feedback during bimanual movements, Coats and Wann (2012) attributed this to decline of proprioceptive abilities in ageing participants. A meta-analysis by Krehbiel et al. (2017) concludes that generally, older adults perform worse on bimanual movement tasks in comparison to younger adults, with natural ability to process sensory information declining due to ageing (Sosnoff and Newell, 2006). Older adults exhibit worse accuracy (Blais et al., 2014, Swinnen et al., 1998); increased variability (Lee et al., 2002), increased movement time (Loehrer et al., 2016, Goble et al., 2010) and overall slower limb movements (Welsh et al., 2007).

Although the exact cause remains to be explored, a correlation between the decline in motor control and cognition decline as we age has been reported by Scherder et al. (2008). Furthermore, the likelihood of neuro-motor impairment also increases with age, with older adults being a majority of stroke sufferers (Newell et al., 2006). Following stroke, over 75% of survivors report chronic upper limb impairments (Lawrence et al., 2001a) . As use of the upper limb comprises a majority of activities of daily living (Davis et al., 1999, Winstein et al., 2016), an impairment to the upper limb can adversely interfere with daily life and function (Veerbeek et al., 2011). Furthermore, in addition to the weakness of paretic limb in reaching and grasping (Trombly, 1993, Krakauer and Carmichael, 2017), inter-limb coupling is also significantly affected following stroke (Lai et al., 2019).

Exploring the role of control processes in coordination of bimanual aiming movements in individuals with mild hemiparesis following stroke, Kantak et al. (2016) reported stroke survivors synchronised bimanual movements by slowing down their unaffected limb to accommodate the hemiparetic limb during the reaching phase of movement, suggesting that the motor system drives to synchronise bimanual movements whilst accommodating for the impaired limb. However, the study does not consider the role of visual demands of the hemiparetic limb in modulating bimanual coupling and task performance. Meadmore et al. (2018a) explored oculomotor control of unimanual reaching movements in stroke survivors and showed that more visual saccades towards the impaired limb side during reach movements, suggesting that the impaired limb requires more visual guidance to targets compared to the unimpaired limb. However, as the study only studied unimanual movements, it is not possible to infer whether the greater requirement of vision of the impaired limb would cause asynchrony between the limbs during bimanual movements.

As well as addition to the knowledge base, upper limb kinematic research in stroke patients has implications for rehabilitation following stroke (Pomeroy and Tallis, 2002, Kantak et al., 2017). Furthermore, stroke survivors consider upper limb recovery a relevant and important rehabilitation goal in maintaining quality of life (De Haan et al., 1993, Winstein et al., 2016). Moreover, rehabilitation to improve performance in activities of daily living in stroke survivors has implications beyond the affected individuals, as it also potentially reduces the burden on health and care services.

To date, no study has monitored visual control of bimanual movements in stroke survivors (or any other patient group); investigation of eye movements during reaching movements is a key objective of this thesis and covers some of the complexities involved in the coordination and control of simultaneous bimanual limb movements when one limb carries a motor impairment.

Broad research questions

This thesis aims to explore how the visuomotor system controls and coordinates unimanual and bimanual reaching movements using overt and covert attention in healthy young adults and in individuals with a limb impairment following stroke. The broad research questions are as follows:

(i) How does the visuomotor system control and coordinate unimanual and bimanual reaching movements using overt visual attention in unimpaired young adults?

(ii) How does guidance of limbs under covert visual attention, (i.e. the absence of visual saccades), affect the control and coordination of bimanual limb movements?

(iii) How does limb impairment following stroke affect control and coordination of unimanual and bimanual reaching movements?

Chapter 2: General methods

Development of a task to study the visual control of movements

A majority of the methods and procedures are common to the studies presented in the thesis, and are presented in this chapter to avoid repetition. Any methodological differences between the studies is presented at the beginning of the relevant chapter.

The experiments were designed to capture movement kinematic measures of the limbs as well as eye movements during a reaching task. Essentially, the goal of the experimentatation was to quantify and analyse how participants coordinated guided unimanual and bimanual reaching movements with and without the availability of visual guidance. Further to capturing the limb and eye movements of participants, the objectives also included measuring the accuracy of movements made.

Apparatus

Below, methodology development of the experimental design is discussed, including process involved in identifying the most suitable hardware as well as software modus for capturing and analysing limb and eye movements.

Eye tracking

During the project design, the aim of the experimenters was to select an eye movement method which would adequately capture horizontal eye movements in a non-obtrusive manner, with high resolution and appropriateness of use across all participant populations, including stroke patients. The following section presents the various methods that were sampled in preliminary experiment design, along with their respective advantages and disadvantages.

EyeTribe

Initially, the EyeTribe (The Eye Tribe ApS, Copenhagen, Denmark), a low cost 20 × 1.9 × 1.9 cm infrared camera based desktop eye tracker was considered. Although a very recent addition to the traditional eye-tracking options available, EyeTribe has been evaluated and reviewed favourably for use in a research setting (Dalmaijer, 2014). The advantages of using an infrared eye tracker would be the relatively low cost (under £100), the lack of necessity of a chin or head rest, and the ability to be used in a naturalistic setting for the experiments as it can be placed in front of the participant. Further advantages of using EyeTribe was its ability to successfully record saccadic eye movement as well as being adept at measuring spatial metrics such as accuracy of eye movements (Ooms et al., 2015).

However, despite the ease of use and set up, the major drawback of using EyeTribe was the relatively low temporal resolution. The resolution of 30Hz and 60 Hz was qualitatively deemed too slow to accurately capture saccades. Alongside the low temporal accuracy, there were also issues with signal loss due to involuntary head movements, and requirement of multiple trials for re-calibration, which would be a challenge to carry out mid-experiment. These issues were confirmed by Raynowska et al. (2018), who found that saccades measured by the EyeTribe did not conform to previously published benchmark requirements (Ramat et al., 2007). Furthermore, as the thesis research's preliminary work progressed, EyeTribe was acquired by a major software company (Oculus, Irvine, CA, USA), in spring 2016 which may have meant facing difficulties with a technical support from the company and lack of license for research use.

ALS head mounted eye tracker

Another option that was available in the lab and considered was a head mounted IR camera-based eye tracker (Model 501, Applied Systems Laboratory, AL, USA). A head-mounted eye tracker has been used in similar research before (Srinivasan and Martin, 2010) and would have been suitable for the intended experimental outcome objectives.

Figure 2.1 ASL Model 501- Head-mounted eye tracker.

The ASL head mounted eye tracker showed greater promise as it tolerated head movements, did not require the participant to keep their head fixed, and appeared to not lose a signal frequently compared to the EyeTribe. The frame rate (60Hz) would be sufficient to capture eye movements as well as the recording of the eye ball, which would indicate the direction of gaze.

However, a major drawback of the ASL eye tracker was its size and obtrusiveness (see Figure 2.1). Preliminary test participants reported physical discomfort from making repeated reaching movements whilst having relatively weighty equipment on their head; which may be tolerated by unimpaired young participants, but would not be optimal for elderly participants and especially stroke patients as it could constrain the ecological validity of the task, making limb movements unnatural and slower.

Another limitation was the relatively modest frame rate (60Hz); although sufficient in capturing saccades, this would not be optimal to record faster saccades and micro-saccades which were likely during the relatively quick (approximately 1 second) movement from the start point to the touch screen. Moreover, the integration of the ASL with the programmed experiment and quantifying the movement of the eye ball was challenging using the ASL software.

Electrooculography (EOG)

Electrooculography, a technique that records eye movements by measuring the change in corneo-retinal potential difference between the front and back of the eye was used. A dipole is created by placement of electrodes on either side of the head, on the right and left side of the respective eye. Eye movement from the centre towards either electrode causes a change in potential difference between the two electrodes, which serves as a measure of the eyes position, with the resulting signal called an electrooculogram (see Figure 2.2 and Figure 2.3).

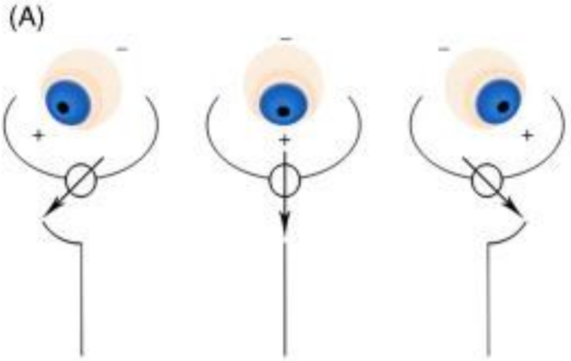


Figure 2.2 Illustration of the eyeball moving to show changes in potential that acts as a steady electrical dipole with a negative pole at the fundus and a positive pole at the cornea. Derived from Barea Navarro et al. (2018).

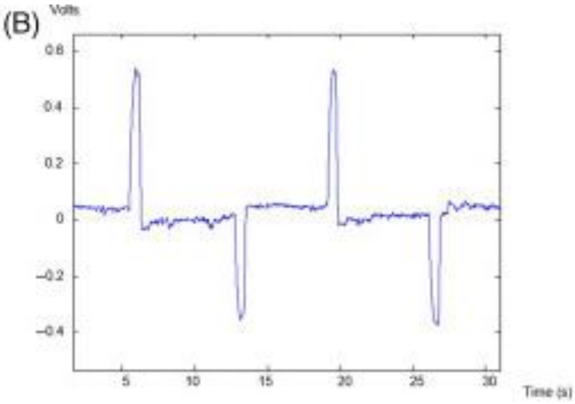


Figure 2.3 The EOG signal corresponding to a right and leftward eye movement obtained with a bioamplifier with gain 1000. derived from Barea Navarro et al. (2018).

Initial reservations for EOG use was the lack of spatial accuracy in output, however, this was not one of the specified dependent variables in the experiment. This inexpensive piece of technology enabled collection of eye movement data at 2000Hz, as well as allowing participants a freedom of degrees of movement in the environment, negating necessity of a fixing participants heads using a bite bar or chin rest. Further advantages included the ease of set up and the unobtrusive nature of the electrodes placement (See Figure 2.4), which were even more marked in the older adults and patient subgroup participants.

EOG allowed measure rightward and leftward eye movements in real time, and was compatible with our existing software (MatLab, Qualisys) and hardware (motion capture cameras) using an amplifier.

Overall, EOG was determined to be the most adequate method of eye movements measurement for the task. As the important elements in terms of dependent variables (i.e. direction of eye movements throughout reaching limb movement) were being captured efficiently using EOG, lack of spatial accuracy was accepted in favour of the temporal resolution and ecological comfort EOG would provide, particularly in the case of older adults and impaired participant groups.

Figure 2.4 Electrode placement on participant: on the outer canthi of the left and right eye, with a grounding electrode in the middle of the forehead.

Kinematic motion capture

Leap motion

Leap motion (software version 2.3.1, Leap Motion Inc, San Francisco, USA), a wireless, virtual reality based upper limb motion capture software and hardware was considered for experimental research use. The device uses infra-red based cameras to cover an approximate of 1m x 1m hemispace, where the cameras capture ~200 frames per second of reflected limb data, which is then synthesized into 3D position data by the software (see Figure 2.5).

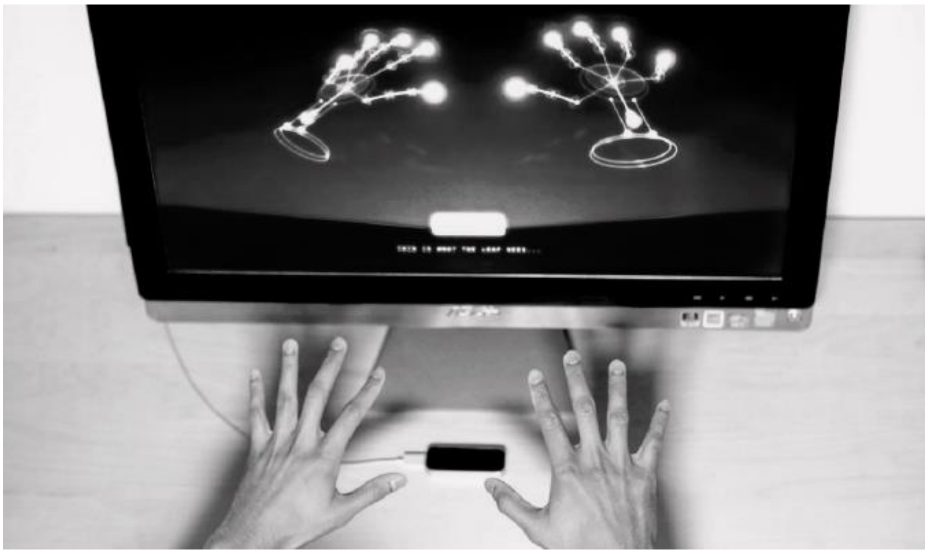


Figure 2.5 Setup and 3D image synthesis using LeapMotion, adapted from Donchyts et al. (2014).

The advantage of the using is its relative ease of set up compared to the other methods mentioned in this section, as well as its real-time feedback and low cost. Another advantage was LMC's spatial accuracy as reported by Bachmann et al. (2014), which although showed higher error than a computer mouse, would be acceptable for the thesis experimental design and analysis. However, the major drawback was the lack of control on the frame rate, as this was not able to be changed by the user, and was pre-programmed to change based on surroundings and environment of the LMC at time of usage. During preliminary set up of experiment, a considerable lag was noticed in the limb movements made and the 3D movement feedback that appeared on the screen. Thus, another method of limb motion capture was considered. Subsequent study by Niechwiej-Szwedo et al. (2018) found that the LMC software has a higher chance in failed limb data collection , whereby around 30% of trials were not recorded. Furthermore LMC is reported to be less accurate and have worse temporal precision in kinematic measures such as movement time and peak velocity.

Qualisys Motion Capture

Available in the department, a three camera motion analysis system (Proreflex, Qualisys, Sweden) enabled collection of three dimensional data of the upper limbs at a sampling rate of 200Hz. A three camera set up was used to ensure markers were not occluded by the monitor screen, as to not affect the systems performance (Chen and Davis, 2002). To ensure accuracy, the motion capture system was calibrated, using a 108mm calibration wand with two markers and a 'L' frame consisting of 4 markers, which enabled definition of the space in which the upper limb movements were taking place. The results of the calibration and accuracy test showed that experimental set up desktop area had a negligible 0.004% marker error.

Target Accuracy measures

A 23-inch LCD touch screen monitor (Dell S2340T) placed on the desktop in front of the participant was used to measure participants movement accuracy. The advantage of using a touch screen as opposed to traditional table-top methods was its relative ease and spatial precision. Calculation of the difference between participants touch positions on screen to the centre of the target enabled computation of the movement accuracy in pixels and centimetres.

A red circle with diameter of 1cm diameter was programmed to appear at the point where the screen was touched during the experimental trials. This ensured that participants were provided with visual feedback of confirmation that they had completed the trial as well as feedback on their spatial accuracy.

Another advantage of using the touch screen was its facility to enable precise temporal data collection from the experiment. For instance, timestamps for experimental trial start time and end time were possible and further temporal accuracy combined with the motion capture system.

Experiment design

Experiment timing and trial events were recorded continuously using a custom made programme built around an Arduino UNO R3 Development Board, a data acquisition board (DAQ 2500, National Instruments Corporation 11500 Mopac Expwy Austin, TX, USA), using the MathWorks software MatLab (3 Apple Hill Drive, Natick, Massachusetts 01760 USA).

Data collection

Experimental set up

First, written informed consent was gained from the participant, which was followed by a practice session. Next, 5mm reflective markers were taped on the index finger nails of the right and left hands of the participants. The finger nail was chosen rather than any other hand part as adherence of the double sided tape is stronger onto the nail surface compared to skin, and secondly to ensure that marker placement was consistent between participants.

As per standard EOG protocol (Brown et al., 2006), self-adhesive surface electrodes were attached to the canthi of the left and right eye, in addition to the ground electrode in the centre of the forehead (see Figure 2.4).

Figure 2.6 Experimental set up using EOG, Touch screen and Motion capture system

Experimental protocol

All participants were seated in a comfortable position in front of the table so that centreline of the screen was aligned with their mid-sagittal plane with the forearms being on top of the desk hands located in a “start” position. To standardize movement ‘start’ location, white visual markers were taped 25 cm apart, 10 cm from the edge of the table, onto the table top to serve as movement start point. In this posture, it was ensured that the participants were free to move their upper limb forward, without the need for trunk involvement. Participants were instructed to start each trial with their index finger on the ‘start’ point, and begin the task, which required them to make reaching movements to targets appearing on the touch screen.

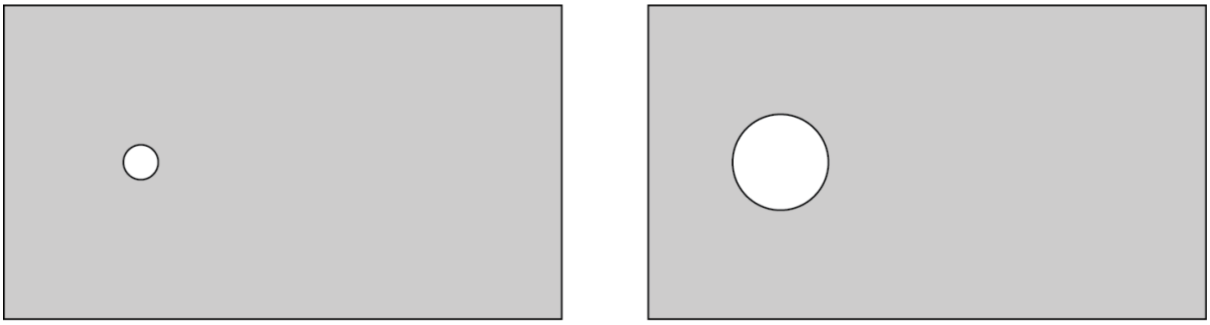
The target object/s appeared on the touch screen, the bottom part of which was 35 cm in front of the start position, tilted back at an angle of 27 degrees from vertical. Subjects were instructed to touch targets on a touch screen using both arms. The left arm was to aim and reach for targets which would appear on the left side of the screen and the right hand to the ones on the right side of the screen. Subjects were instructed to aim and touch the centre of the target circles as quickly and accurately as possible. No other explicit instructions were given to the participant about the expected speed or sequence of movements or behaviour. The end of each trial was identified at the point where the index finger of the participant touched the target on the screen, this included trails where the targets were missed. The targets appeared on screen for a set time (3 seconds for experiment 1 & 2, and 7 seconds for experiment 3), the screen moved onto the next trial after this time had elapsed in cases where the target had not been touched.

The task was self-paced and began with an on screen “participant ready to start?” prompt on screen, which was followed by the experimenter confirming so. As the task began, a fixation cross was presented in the centre of the screen for a randomized period between 1000 and 3000 ms; the fixation cross then disappeared and was followed by the visual targets. Each trial lasted approximately 5 to 7 seconds, including the time where the fixation crosses was visible and the time available to the participants to return their fingers to the ‘start’ position. A practice session was run to enable the participants to familiarize themselves with the task, consisting of each condition being run once (eight practice trials in total). The practice session was followed by the experimental session in which each task condition was performed for 10 repetitions, resulting in 80 experimental trials in total. As the participant touched the screen, the touch points (i.e. where the screen was touched) were highlighted in red for 1000 ms before the targets went off screen; this served as visual feedback of accuracy for the participant’s performance on each trial. The order of trials and therefore experimental conditions was randomised to prevent any learning effects taking place. Furthermore, participants were given the opportunity to request to pause the experiment at any point for taking breaks.

Stimuli

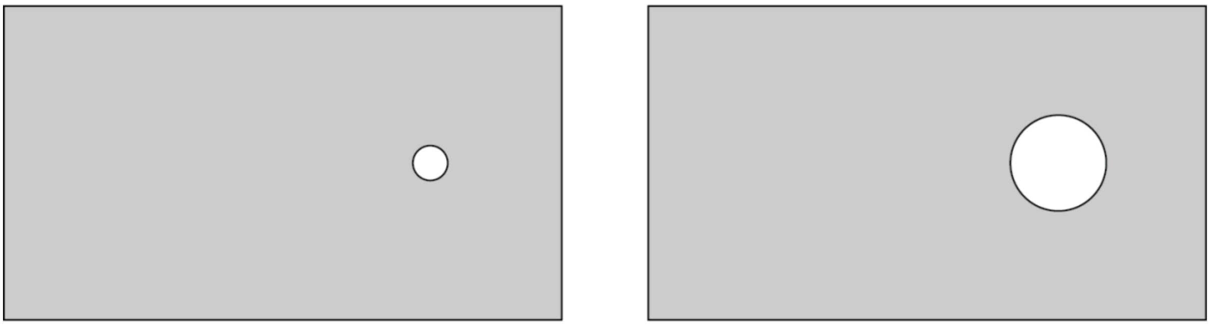
Targets could be either small (diameter = 2cm) or large (diameter = 10cm), the latter considered to have a lower index of difficulty. Where single targets appeared, unimanual movements were required. Where two targets appeared, bimanual movements were required. In this case, targets’ size determined whether the condition was either congruent (i.e. targets the same size) or incongruent (i.e. targets of different size). There were eight experimental conditions in total (see fig 2.7 & fig 2.8). In unimanual the independent variable was the size of the target (either small or large). In bimanual conditions, the independent variables were congruence and target size.

For all conditions, targets were offset laterally and vertically from their original/ previous position on screen at random by a maximum of 200 pixels for each trial, this was to force visual control on to the targets and to ensure no motor learning effects took place as the trials progressed. For bimanual conditions the left and right targets remained an equal distance from each other whilst moving equidistantly from the original/ previous on-screen position.



Unimanual, Left Hand, Small target

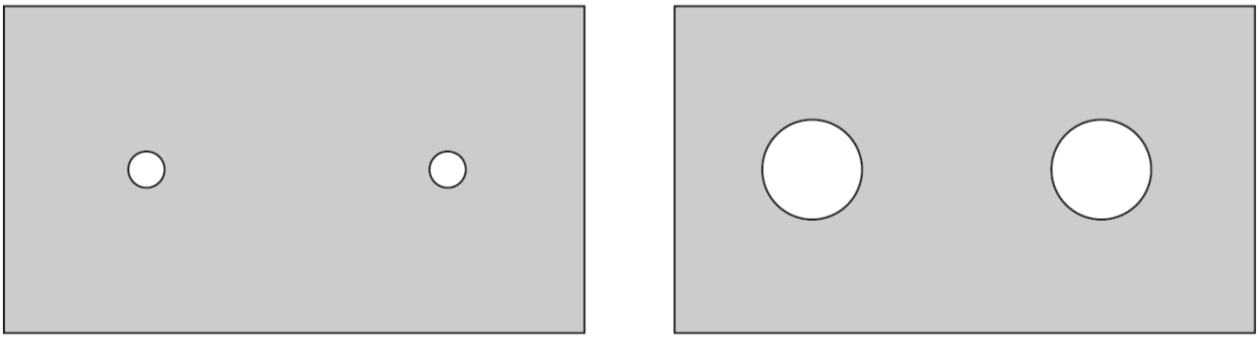
Unimanual, Left Hand, Large target



Unimanual, Right Hand, Small target

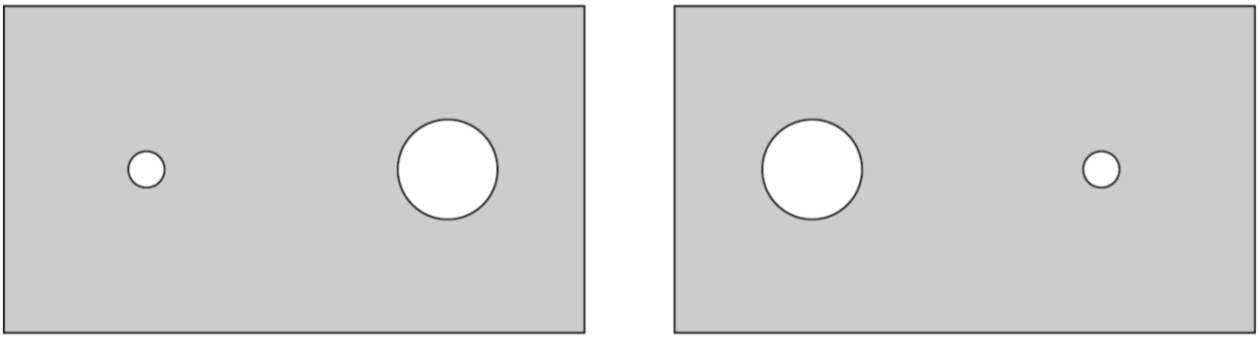
Unimanual, Right Hand, Large target

Figure 2.7 Visual stimuli used in experiment for unimanual conditions



Bimanual, Small targets

Bimanual, Large targets



Bimanual, Left Small/ Right Large targets

Bimanual, Left Large/ Right Small targets

Figure 2.8 Visual stimuli used in experiment for bimanual conditions

Data Analysis

Kinematic data analysis

The data collected by the motion capture system was captured by Qualisys Track Manager, (Qualisys, Sweden, www.qualisys.com), a Windows based data acquisition software, and then exported and analysed via MatLab (Mathworks). The data were filtered using a 5th order low-pass Butterworth filter with a cut-off frequency of 20Hz by to smooth the data collected. Following this, Matlab commands were used to obtain the following dependent variables.

Kinematic dependent variables

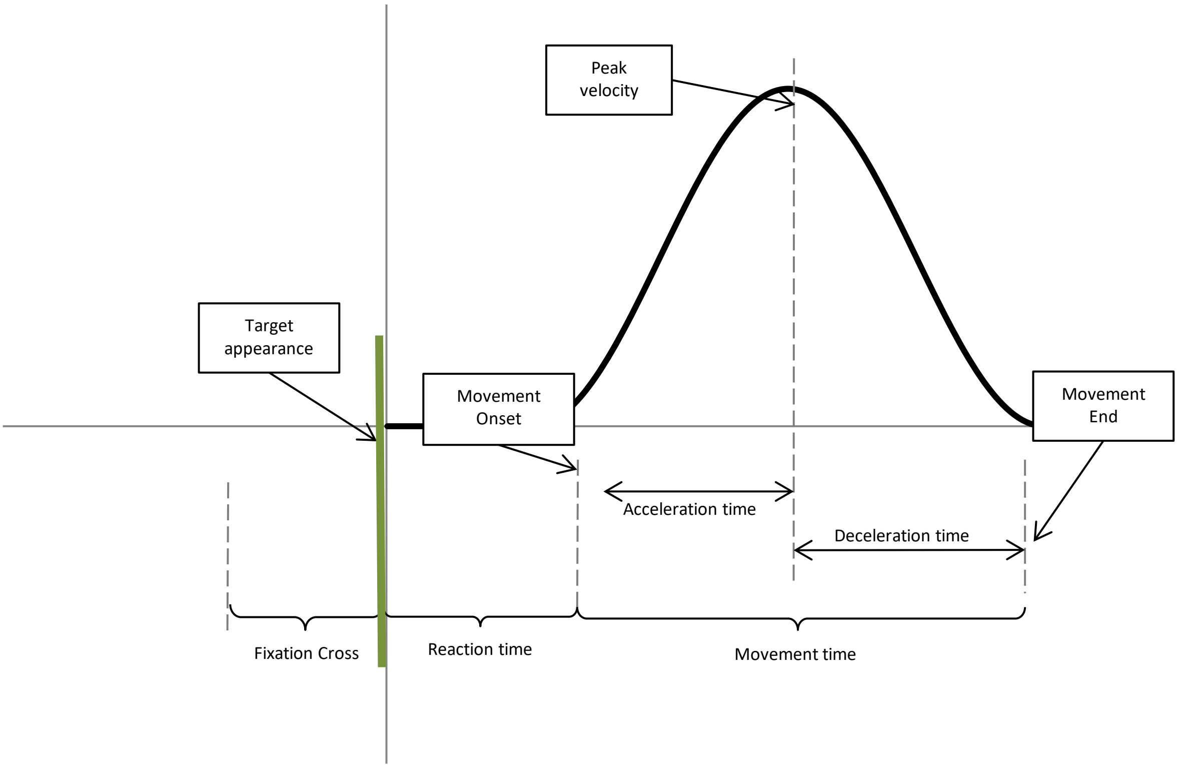


Figure 2.9 Illustration to show how kinematic variables were derived

Below, the variables selected to describe movement performance are given along with details as to how each was derived.

Limb movement measures

Reaction time (RT): time (ms) from target onset (touchscreen) movement onset (first frame when the speed exceeds 50mm/s).

Movement time (MT): time (ms) from movement onset to movement end (touchscreen).

Response time (ResT): time (ms) from target onset to movement end i.e. (i) + (ii).

Acceleration time (AT): time (ms) from movement onset to time that peak speed (see below) is reached.

Peak speed (PS): the highest speed (mm/s) reached during the limb's movement towards the target.

Deceleration time (DT): time (ms) from the frame peak speed reached to movement end.

Target acquisition error (TE): the distance (mm) from centre of target circle to the touch point.

Coupling relations between the limbs

For bimanual conditions, of interest was the 'coupling' between the limbs. This included understanding the absolute synchrony between the limbs as well as any lateralised bias that may have emerged. Limb synchrony was measured using the following variables:

Absolute mean lag: the time (in ms) separating the limbs at critical time points, the time lag reflects the absolute size of the difference between the timing of the two hands regardless of direction.

Signed mean lag: The direction of asynchrony between the limbs was captured. The timings of the right hand were indexed to those of the left hand, which gave the time differential between the two hands and the direction this was in. A negative lag represented a left-hand lead while a positive lag represented a right-hand lead.

Lag between limbs was calculated on a trial by trial basis as per recommendations by previous researchers in the field (Coats and Wann, 2012, Bruyn and Mason, 2009, Miller and Smyth, 2012), as mean data alone will not provide sufficient information about the nature of coordination between limbs, and indeed about the direction of temporal bias between the two limbs.

Inter-limb synchrony was measured at three specific movement landmarks:

Movement onset; Time of peak speed; Movement end. Here, the relative position of the left limb compared to the right limb (for relative directional lag) was calculated; in addition to the absolute difference between the two limbs (the absolute non-directional time difference), which were then used to calculate means of the inter-limb lags.

Electrooculography data analysis

Horizontal eye-movements were recorded using electrooculography (EOG), with signals sampled at 2000Hz, amplified and band pass filtered (0.1–30 Hz) using an AC preamplifier (Grass Instruments LP122)

For eye movement analysis, saccade onset was defined as the point at which the Electroculogram signal velocity crossed a threshold of 0.1 for rightward eye movements or was below -0.1 for leftward eye movements (see Figure 2.10 for illustration); with right ward eye movements being assigned a positive value and left as a negative value.

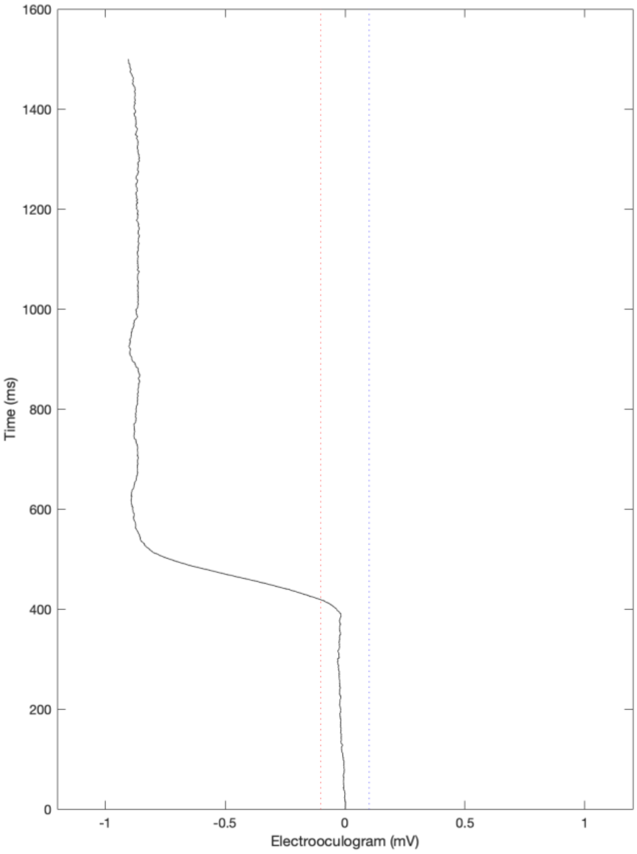


Figure 2.10 Illustration of EOG data processing for leftwards eye movement

Eye movements during the task were recorded using the variable: Proportional gaze during response time, which was defined as 'Time spent looking *Left* or *Right* as a proportion of Response Time'. Using proportional gaze time rather than actual gaze time allowed for the values to be normalised for statistical analysis across different conditions and participant data.

Proportional gaze throughout response time and terminal gaze were expressed as -1 values for left sided eye movements, and +1 for right sided eye movements. The means were computed using the mean measure of time that vision was directed to each side during response time.

Statistical analysis

Kinematic statistical analysis

To examine differences with respect to congruence of target(s), side of limb and size of target(s) for limb kinematics variables, individual means were computed for every dependent variable for every participant for both hands and entered into a repeated measures analysis of variance (ANOVA). The main effects of task conditions on dependent variables were examined using a 3 x 2 x 2 ANOVA; with the factors of *Congruence* (unimanual vs. bimanual congruent vs. bimanual incongruent), *Hand* (dominant vs. non dominant) and *Size of target* (small vs. large).

For all dependent variables, sphericity was assumed and, F and p values are reported for within subjects main effects, with a statistical significance value of $\alpha = 0.05$. For variables with more than 2 levels where significant main effects were found, pairwise comparisons were used to compare means. In these instances, Bonferroni post hoc analyses were carried out and Bonferroni adjusted p values are reported. Interactions were explored using inferential statistics.

Inter-limb coupling statistical analysis

To calculate statistical significance in difference in signed mean lag, a 2 x 2 x 2 ANOVA with repeated measures was conducted with factors of *Congruence* (incongruent vs. congruent) and *Size of Left Target* (small vs large) and a third factor termed '*Bias'* (Initial value vs. it's additive inverse). Absolute synchrony would be indicated by a value of zero, thus comparison of the lag value to 'zero value' was considered. However, a more conservative and statistically stringent approach was adopted, whereby the lag times initial value sign was changed for all the data and compared with their 'inverse' representation, which provided more variability in the comparison.

A statistically significant effect of *Bias* suggested that a lag in a given direction was reliably different from zero (where no lateralised bias is observed). For all ANOVAs presented, resulting interactions were explored via simple effects; these analyses were conducted using Bonferroni adjustment.

EOG statistical analysis

For eye movement (EOG) analysis a 2 x 2 x 2 ANOVA was conducted with the variables of *Congruence* (congruent vs. incongruent) and *Left Target Size* (small vs. large) for bimanual conditions. Using the size of left target as a variable adequately captured the differences between congruence and the target sizes, and thus covered all 4 bimanual conditions for analysis. As before, to ascertain whether eye movements across participants showed a reliable directional bias (i.e. different from the 50:50 ‘equal’ situation) a third factor ‘*Bias’* was included. Signed data entered for analysis were reversed (inverted); only in cases where a *Bias* effect was found did we interpret data as being reliably biased in a given direction. These analyses were conducted using Bonferroni adjustment, with resulting interactions explored via simple effects.

Ethical statement

The project procedure was in accordance with the ethical standards stated in the Declaration of Helsinki and approved by the University of Birmingham Science, Technology, Engineering and Mathematics (STEM) Ethics and Research Committee (ERN15 0557). Written informed consent was obtained from all participants prior to their inclusion in the study.

Chapter 3: On the relations between overt visual attention and between-limb asynchrony for bimanual aiming movements

The current chapter is part of a submission to Experimental Brain Research journal. The format of the results section has been modified from the originally submitted manuscript in response to a reviewer's comments.

Abstract

Although synchrony between the limbs is an often-cited feature of bimanual coordination, recent studies have highlighted the small asynchronies that can occur. The visual demands of any given bimanual task are thought to be central to the emergence of asynchrony but the relationship between vision and related bimanual performance remains largely unexplored. In this study, hand and eye movements were measured while individuals made either unimanual or bimanual reach-to-point (aiming) movements. Bimanual movements could be either congruent (same sized targets) or incongruent (different sized targets). Resulting hand data showed many of the typical patterns of movement previously reported. However, where asynchrony emerged, particularly in the latter stages of movements, clear relationships with vision became apparent. Firstly, there was a tendency for the hand reaching towards the more difficult target to lead the other limb. Furthermore, whether movements were congruent or incongruent, the side to which participants selected to primarily direct vision was associated with a lead of the corresponding limb. The results show how the visuo-motor system balances its apparent drive for synchrony in the planning and execution of bimanual movements, with the need to visually guide the

limbs to two different locations. However, where bias in visual guidance occurs, this also appears to determine the direction of asynchrony between the limbs.

Introduction

Being able to use both hands in a coordinated manner is critical to performing everyday functions; for example, consider using a knife and fork during eating. This study is concerned with how humans use vision to control moving both upper limbs at the same time. Bimanual movements demonstrate a strong tendency to be coupled, even when tasks require each limb to make movements to targets that differ in size (Kelso et al., 1979, Jackson et al., 1999). However, as vision can only be directed towards one target at a time, such circumstances create a challenge for the individual as to where to direct vision as the movements unfold. This challenge may be considered to have a strong competitive element with each limb/target *competing* for visual resources (Duncan et al., 1997).

For unimanual movements, factors influencing the so-called *index of difficulty* (IoD) relate to target features. Accordingly, it has long been known that target size and target distance have a systematic effect on movement time, as explained by Fitts' Law (Fitts, 1954). For bimanual movements to separate targets, this relationship holds where these are made to targets with the same IoD, although there is an overall *cost* of performing two movements at the same time (i.e. both movements are slower) (Jackson et al., 1999). However, where bimanual movements are made to targets with differing IoDs, the overriding influence exerted by coupling ensures that Fitts' Law is violated. In such cases, the limb moving to the easier target tends to be slowed so that movement starts and ends at the same time as the limb moving towards the more difficult target (Kelso et al., 1979, Jackson et al., 1999). Importantly, while these movements are ostensibly coupled, many studies have highlighted the small asynchronies that emerge and become more pronounced during the latter stages of movement. These asynchronies are thought to be driven, at least partly, by the visual requirements posed by the related targets (Fowler et al., 1991, Riek et al., 2003, Bruyn and Mason, 2009, Hesse et al., 2010, Srinivasan and Martin, 2010, Miller and Smyth, 2012).

In support of the above, Miller & Smyth (2012) showed temporal synchrony to be enhanced in the absence of visual feedback. Furthermore, where visual fixation is constrained (e.g. where participants fixate a midpoint between two targets or on just one target), synchrony is greater than in the *free view* condition (Hesse et al., 2010, Jackson et al., 2002a) while accuracy is diminished (Bruyn and Mason, 2009, Jackson et al., 2002a); see Chapter Four. As Srinivasan and Martin (2010) suggest, “the relationship between gaze orientation and hand movements seems to reflect a trade-off between accuracy and synchronization” (pp. 403). While these more recent studies have highlighted that asynchrony during bimanual activity is modulated by the task-related demands on vision, the nature of this relationship is not well understood.

As well as the demands of the task, performance may also be modulated by the relative skill of the limbs involved. For unimanual movements, an individual may be relatively fast and more accurate to perform the same movement with their dominant compared with their non-dominant limb (Roy et al., 1989). For bimanual movements, how individuals manage these *internal* issues while also managing the varying task demands (*external* issues) that affect movement difficulty also remains relatively unexplored. For example, where the target-related IoD is identical for each hand in a bimanual task, one might expect attention to be directed towards the non-dominant (less skilled) limb. However, early research suggested the opposite was true (Peters, 1981). Subsequently, Honda (1982) had right-handed individuals make bimanual reaching movements to the same sized targets and similarly found a strong tendency for initial rightward eye movements. More recent research, while not measuring eye movements, also strongly suggests a rightward bias of attention during bimanual reaching movements (Buckingham and Carey, 2009, Buckingham et al., 2011).

However, studies including a more detailed analysis of eye movements (i.e. they measure overt attention) during a bimanual aiming task with right handers found terminal eye movements (i.e. the direction that vision was directed at the time movements were completed) to be directed to the left (non-dominant) side when the IoD of targets was identical (Riek et al., 2003). More recently, Srinivasan & Martin (2010) also found terminal eye movements to be directed towards the left (non-dominant) side during bimanual aiming movements where the target IoD was the same. In both the above studies (Riek et al., 2003, Srinivasan and Martin, 2010), tasks were designed in such a way as to constrain accuracy (i.e. error was not possible) and this may have given rise to the 'hover' phase reported. Accordingly, participants invariably interrupted the movement of the leading limb just shy of its target until the other limb caught up before completing the final part of both movements synchronously.

Together, it appears that studies to date are inconsistent with regards to how visual resources are allocated to guide bimanual movements. While directing vision to a given target enhances accuracy of the related movement during bimanual activity, whether there is any predictable *knock*-on effect of this for coupling (i.e. is coupling disrupted in a predictable way?) is unclear. Perhaps one of the reasons for this is that surprisingly few studies have attempted to measure eye movements during visually-guided bimanual tasks.

Addressing this issue, the current study aimed to explore eye and hand movements while individuals make either unimanual or bimanual aiming movements to targets with either the same or different IoDs. It was expected that resulting data would show many of the typical characteristics of bimanual movements previously reported. Accordingly, bimanual movements were expected to be slower (and less accurate) than unimanual movements. Additionally, it was expected that coupling would be maintained across both congruent and incongruent bimanual movements. Further, by measuring the direction of gaze during bimanual movements, it was expected that new information would emerge about the relationship between vision and bimanual coordination. Where bimanual movements were incongruent (i.e. had different IoDs), it was expected that gaze would be biased towards the more difficult side and that the related movement would be more accurate as a result. Due to contrasting previous findings (Honda, 1982, Riek et al., 2003, Srinivasan and Martin, 2010), it was unclear whether dominance would have any additional modulating effect on gaze direction as well. Finally, the study aimed to further examine the small between-limb asynchronies that have been a feature of a number of related studies (Fowler et al., 1991, Riek et al., 2003, Bruyn and Mason, 2009, Hesse et al., 2010, Srinivasan and Martin, 2010, Miller and Smyth, 2012). Of particular interest was, (i) whether the overall magnitude of any asynchrony was related to the relative difficulty of conditions? And, (ii) whether the direction of any asynchrony (i.e. whether one limb would reliably lead the other) was related to the relative difficulty of component unimanual movements?

Methods

Participants

Ten right-handed and nine left-handed individuals aged between 18 and 23 years old participated in the study as unpaid volunteers. All participants had normal vision and had no known neurological or musculo-skeletal disorders. Handedness was confirmed using the Edinburgh Handedness Inventory (Oldfield, 1971).

Apparatus, Procedure, Dependent variables and Statistical analysis

The Apparatus, Procedure, Dependent variables used and statistical analysis conducted was as detailed in Chapter 2 and has been omitted from this section to avoid repetition.

Additional analysis

In addition to the statistical analysis detailed in Chapter 2, a series of correlation analyses were conducted in experiment 1 to explore relationships between *Target Error* (limb performance), *Signed lag* at movement end (Synchrony) and *Proportional gaze during response time* (gaze behaviour). Values for *Signed lag* and *Proportional gaze during response time* were already computed. *Target Error* value was derived by combining left and right hand *Target Error* value to produce a *Target Error Index,* with resulting negative values indicating greater accuracy for the left hand and positive values indicating greater accuracy for the right hand.

Ethical statement

The project was reviewed and approved by the University of Birmingham's Science, Technology, Engineering and Mathematics Ethical Review Committee. Participants provided written informed consent prior to taking part.

Dependant variables

Limb movement measures

Reaction time (RT): time (ms) from target onset (touchscreen) movement onset (first frame when the speed exceeds 50mm/s).

Movement time (MT): time (ms) from movement onset to movement end (touchscreen).

Response time (ResT): time (ms) from target onset to movement end i.e. (i) + (ii).

Acceleration time (AT): time (ms) from movement onset to time that peak speed (see below) is reached.

Peak speed (PS): the highest speed (mm/s) reached during the limb's movement towards the target.

Deceleration time (DT): time (ms) from the frame peak speed reached to movement end.

Target acquisition error (TE): the distance (mm) from centre of target circle to the touch point.

Coupling relations between the limbs

Absolute and relative inter-limb synchrony was measured at Movement onset; Time of peak speed; Movement end in milliseconds (ms).

Direction of gaze

This was calculated as a proportion of total response time for unimanual conditions and bimanual conditions.

Results

Limb movements

Table 3.1 provides mean (and standard error) values for limb movement measures and notes the significant main effects and interactions found for each. Across all these analyses *Side* (dominant vs. non-dominant hand) did not feature as a significant main effect or in any interactions; data presented were therefore collapsed across this factor.

	Unimanual		Bimanual		Bimanual		Effects
	Small	Large	Small	Large	Small	Large	
Reaction time	445 (13)	419	491 (23)	448	491	481 (22)	Cond, Size,

Acceleration time	159 (8)	154 (8)	175 (9)	170 (9)	176 (8)	175 (9)	Cond	
Peak speed	1244 (58)	1311	1117	1214	1155	1152 (63)	Cond,	Size,
Movement time	710 (38)	585	990 (67)	716	828	886 (62)	Cond,	Size,
Deceleration time	550 (35)	429	812 (63)	546	646	709 (58)	Cond,	Size,
Response time	1154 (46)	1012	1483	1168	1325	1362 (76)	Cond,	Size,

Table 3.1. Mean (and standard error) values and significant effects as a function of Condition and Size for limb movement measures.

Statistical analysis of several kinematic measures revealed a significant main effect of *Condition* (see Table 3.2 for related pairwise comparisons) and *Condition* x *Size* interaction (see Table 3.1 for the individual *Size* effects for each condition). These significant main effects and interactions largely replicate the data of previous bimanual movement studies and highlight two important previously established findings. Firstly, data highlight the *cost* of undertaking bimanual compared with unimanual movements; bimanual movements were slower than unimanual movements. Secondly, while movements to small targets were slower during unimanual and bimanual congruent movements (consistent with Fitts' Law), this was not the case for bimanual incongruent movements. In the latter case, response times were comparable for small and large targets. In addition, the component measures of movement time and deceleration time showed significantly shorter values for *small* targets.

Measure	***Main effect***	***Comparison***	***N***	***Mean***	***SEM***	***p***
Reaction time	F(2,36) = 13.65,	Uni – BiCon	19	-37.192	12.120	.020

	p < 0.001,	Uni – BiInc	19	-54.237	12.727	.001
	η_p^2 = 0.431	BiCon – BiInc	19	-17.045	5.411	.017
Acceleration	F(2,36) = 10.51,	Uni – BiCon	19	-16.016	4.942	.014
	p < 0.001,	Uni – BiInc	19	-18.808	5.424	.008
	η_p^2 = 0.369	BiCon – BiInc	19	-2.792	2.233	.681
Peak speed	F(2,36) = 42.61,	Uni – BiCon	19	111.627	17.961	< 0.001
	p < 0.001,	Uni – BiInc	19	123.887	16.481	< 0.001
	η_p^2 = 0.703	BiCon – BiInc	19	12.259	7.870	.410
Movement time	F(2,36) = 58.82,	Uni – BiCon	19	-205.941	26.446	< 0.001
	p < 0.001,	Uni – BiInc	19	-209.514	25.951	< 0.001
	η_p^2 = 0.766	BiCon – BiInc	19	-3.573	9.730	1.000
Deceleration	F(2,36) = 54.69,	Uni – BiCon	19	-189.237	24.605	< 0.001
	p < 0.001,	Uni – BiInc	19	-187.939	24.350	< 0.001
	η_p^2 = 0.752	BiCon – BiInc	19	1.297	10.113	1.000
Response time	F(2,36) = 56.09,	Uni – BiCon	19	-.243	.032	< 0.001
	p < 0.001,	Uni – BiInc	19	-.261	.031	< 0.001
	η_p^2 = 0.757	BiCon – BiInc	19	-.018	.015	.732

Table 3.2. Paired comparisons for the Condition factor showing the difference between unimanual (Uni), bimanual congruent (BiCon) and bimanual incongruent (BiInc) movements.

		Condition		
Measure	***Condition x Size***	***Unimanual***	***Bimanual congruent***	***Bimanual Incongruent***
Reaction time (ms)	$F(2,36) = 3.16$, $p = 0.05$, $\eta_p^2 = 0.149$	$F(1,18) = 12.79$, $p = 0.002$, $\eta_p^2 = 0.415$	$F(1,18) = 12.00$, $p = 0.003$, $\eta_p^2 = 0.400$	$F(1,18) = 1.92$, $p = 0.19$, $\eta_p^2 = 0.096$
Acceleration time (ms)	$F(2,36) = 0.34$, $p = 0.72$, $\eta_p^2 = 0.018$	n/a	n/a	n/a
Peak speed (mm/s)	$F(2,36) = 17.85$, $p < 0.001$, $\eta_p^2 = 0.498$	$F(1,18) = 40.77$, $p < 0.001$, $\eta_p^2 = 0.694$	$F(1,18) = 39.58$, $p < 0.001$, $\eta_p^2 = 0.687$	$F(1,18) = 0.09$, $p = 0.77$, $\eta_p^2 = 0.005$
Movement time (ms)	$F(2,36) = 65.85$, $p < 0.001$, $\eta_p^2 = 0.785$	$F(1,18) = 98.16$, $p < 0.001$, $\eta_p^2 = 0.845$	$F(1,18) = 72.00$, $p < 0.001$, $\eta_p^2 = 0.800$	$F(1,18) = 18.66$, $p < 0.001$, $\eta_p^2 = 0.509$
Deceleration time (ms)	$F(2,36) = 65.94$, $p < 0.001$, $\eta_p^2 = 0.786$	$\mathrm{F}(1,18) = 106.27$, $p < 0.001$, $\eta_p^2 = 0.855$	$F(1,18) = 71.30$, $p < 0.001$, $\eta_p^2 = 0.798$	$F(1,18) = 20.21$, $p < 0.001$, $\eta_p^2 = 0.529$
Response time (ms)	$F(2,36) = 48.35$, $p < 0.001$, $\eta_p^2 = 0.729$	$F(1,18) = 113.04$, $p < 0.001$, $\eta_p^2 = 0.863$	$F(1,18) = 61.47$, $p < 0.001$, $\eta_p^2 = 0.773$	$F(1,18) = 4.05$, $p = 0.059$, $\eta_p^2 = 0.184$

Table 3.3. Simple effects resulting from the Condition x Size interactions that result for limb movement measures.

Target error

Across all conditions, the dominant limb performed with less error (0.49mm) than the non-dominant limb (mean = .55mm) leading to a significant main effect of *Side*, F(1,18) = 9.97, p = .005, η_p^2 =0.357. There was also significant main effects of *Condition*, F(2,36) = 30.33, p < .001, η_p^2 =0.628, *Size*, F(1,18) = 109.30, p < .001, η_p^2 =0.859 and a *Condition* x *Size* interaction, F(2,36) = 20.75, p < .001, η_p^2 =0.535. The latter is best explained by referring to Fig. 2. As might be expected, participants deviated further from the centre of large targets (i.e. they showed greater error) than small targets, whatever the condition. In addition, bimanual movements resulted in greater overall error than unimanual movements. However, while the two bimanual conditions did not differ overall in terms of error, the pattern of errors was different. While the accuracy cost of making congruent bimanual movements was borne by both limbs (p < .005 for small, p < .001 for large, both corrected), the accuracy cost of making incongruent bimanual movements was all borne by the limb moving to the large target; i.e. accuracy for small targets was comparable for unimanual and bimanual incongruent conditions (p = 1.0. corrected).

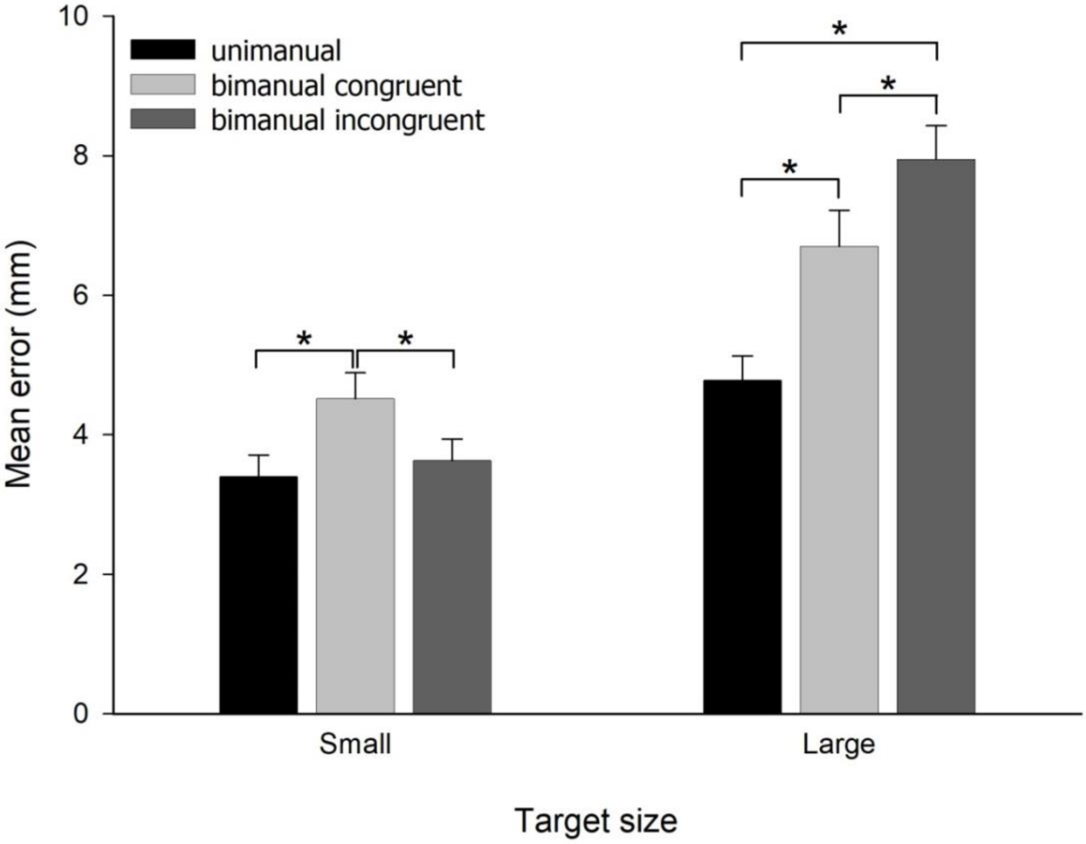


Figure 3.1 Mean target error as a function of condition for each of the target sizes. Error bars denote the standard error of the mean. Asterisks denote statistical significance.

Limb coupling

Fig. 3.2 presents mean lag data reflecting temporal coordination between the limbs at movement onset, as the limbs reached peak speed and at movement end. For the first two of these measures, a 2x2 (Congruence x Dominant Target Side) ANOVA revealed no significant main effects and no interactions supporting the strong coupling of bimanual movements. Indeed, mean values for all conditions were within 12ms of zero (i.e. perfect synchrony) at these time points. However, at movement end, asynchrony emerged and the ANOVA revealed an interaction, F(1,18) = 11.45, p = .003, η_p^2 =0.389. For congruent movements, the size of targets had no effect on coupling, F(1,18) = .68, p = .42, η_p^2 =0.036. However, for incongruent movements, there was a marked lead for the limb moving to the small target with a significant effect of Dominant Target Size, F(1,18) = 10.36, p = .005 uncorrected, η_p^2 =0.365.

The more pronounced asynchrony for incongruent bimanual movements at movement end was borne out by the absolute lag data. Here, the mean absolute lag was significantly larger for incongruent (106ms) compared with congruent (67ms) movements, F(1,18) = 14.89, p = .001, η_p^2 =0.453.

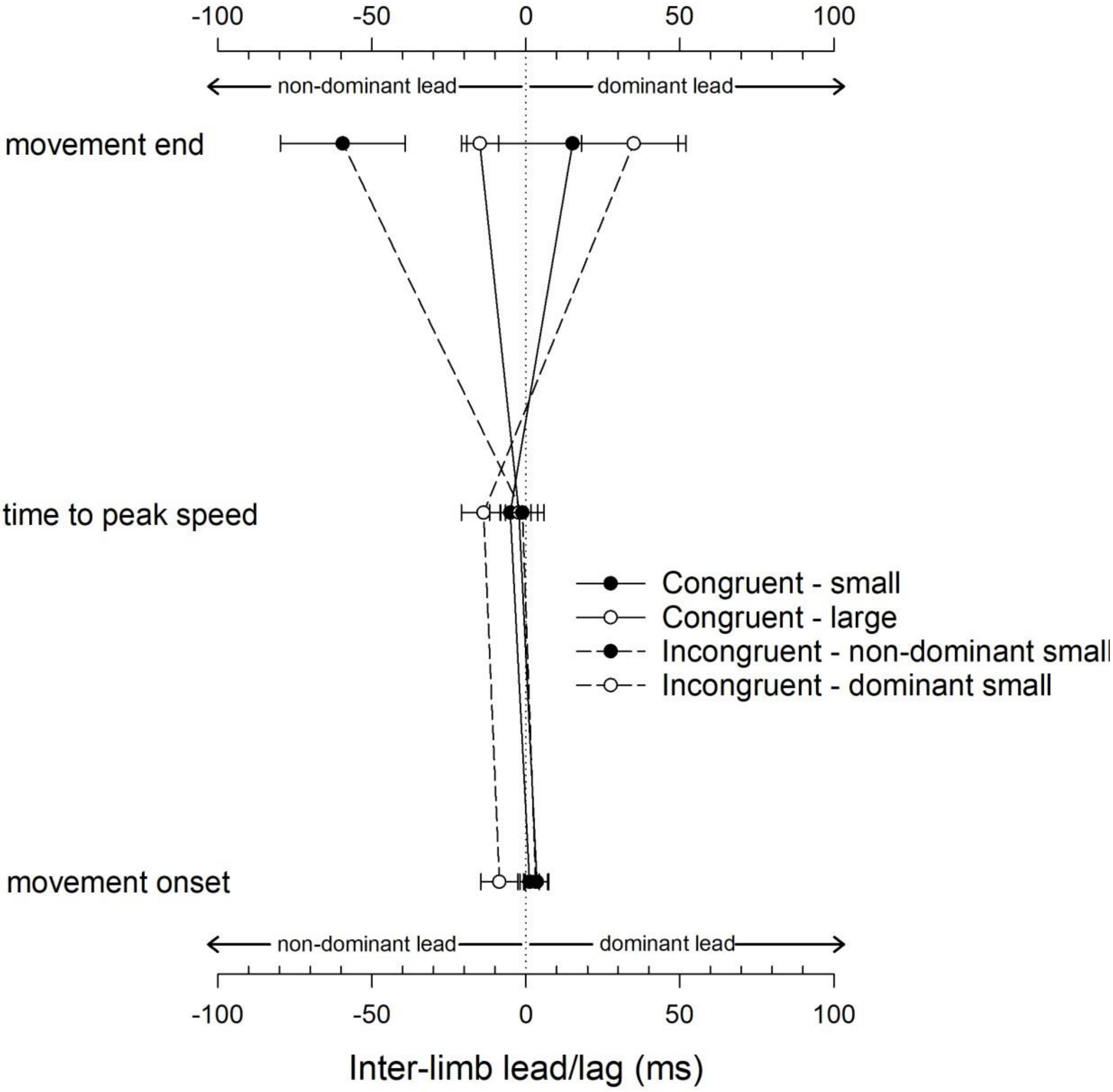


Figure 3.2 Inter-limb asynchrony (lead/lag) shown as a function of congruence and phase of movement landmark. Error bars denote the standard error of the mean. Negative values indicate a non-dominant hand lead; positive value indicates a dominant hand lead.

Eye movements and relations with other measures

Time spent looking to either the non-dominant or the dominant side was measured as a proportion of response time; accordingly, values of -1 and +1 would indicate that the whole response time was spent directing gaze to the non-dominant and dominant sides respectively. However, given that trials always began with participants fixating centrally, values never reached -1 or +1 but still provided a measure of bias in one direction or the other. For unimanual movements, participants typically made a single saccade in the direction of the single target. Mean values were -.72 and .68 for the non-dominant and dominant sides respectively resulting in a marked *Side* effect, F(1,18) = 1820.99, p < .001, η_p^2 =0.990. There was no effect of *Size* and no interaction.

For bimanual movements, participants often made multiple saccades but our measurement approach allowed biases to emerge (see Fig. 3.3). Our primary interest here was whether any lateralised bias was reliable. As a more conservative measure of this than simply comparing with zero, a comparison was conducted for each condition with the corresponding inverted data. For congruent conditions, although mean values were towards the dominant side, this was only reliable where targets were large (small, t(18) = 1.60, p = .13; large, t(18) = 2.60, p = .018). For incongruent targets, bias was far more pronounced. When the small target was on the dominant side, significantly more time was spent looking towards that side, t(18) = 6.32, p < .001. Similarly, there was a strong bias to the non-dominant side when the small targets was on that side, t(18) = -5.92, p < .001.

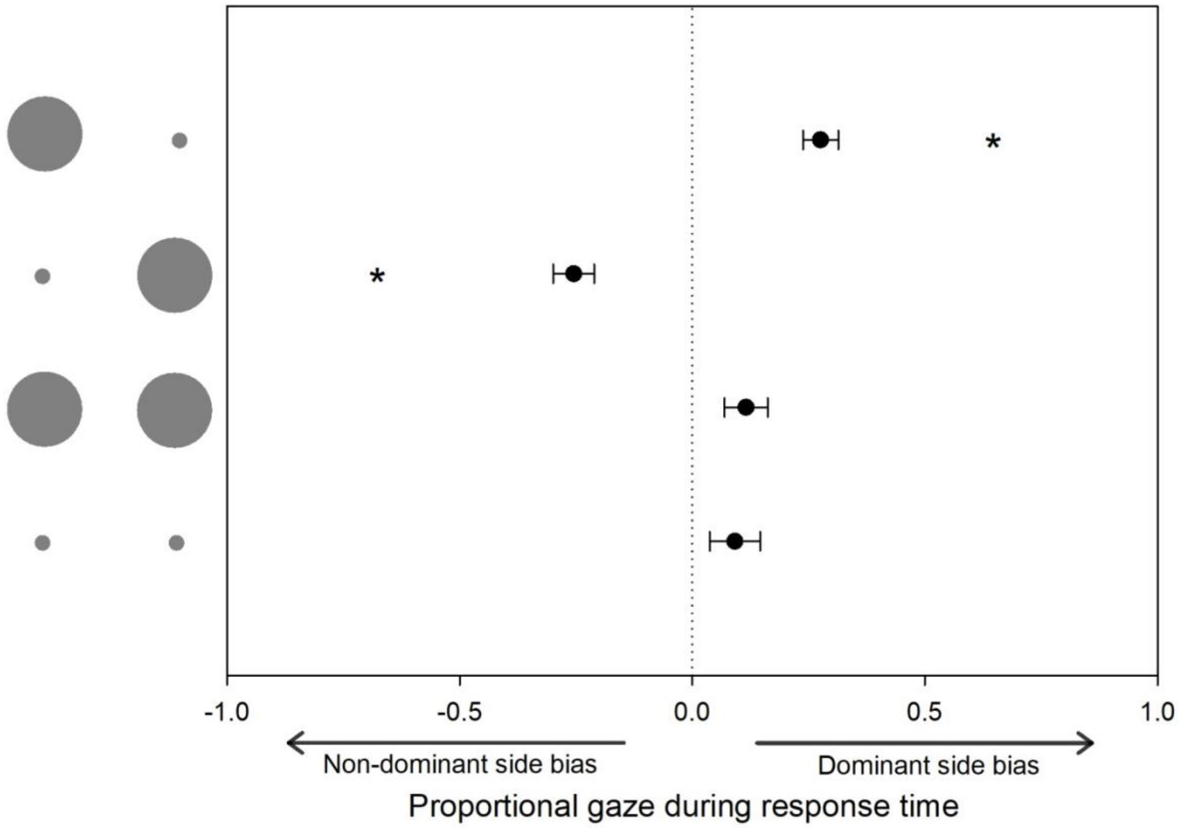


Figure 3.3 Direction of gaze as a proportion of total response time. Error bars denote the standard error of the mean. Negative values indicate gaze bias to the non-dominant side; positive values indicate a gaze bias to the dominant side. Asterisks denotes a statistically significant difference from the additive inverse.

Finally, in order to further highlight the orienting biases reported above and the accompanying inter-limb asynchrony also observed, Fig. 3.4 presents bivariate data for these two measures. Inspection of this figure underlines the pattern of data referred to above; where participants' oriented towards one side, the corresponding limb was the leading limb at movement end. Fig. 3.5 shows the corresponding relationship between orienting bias and accuracy; the more accurate limb was on the side that orienting was biased towards.

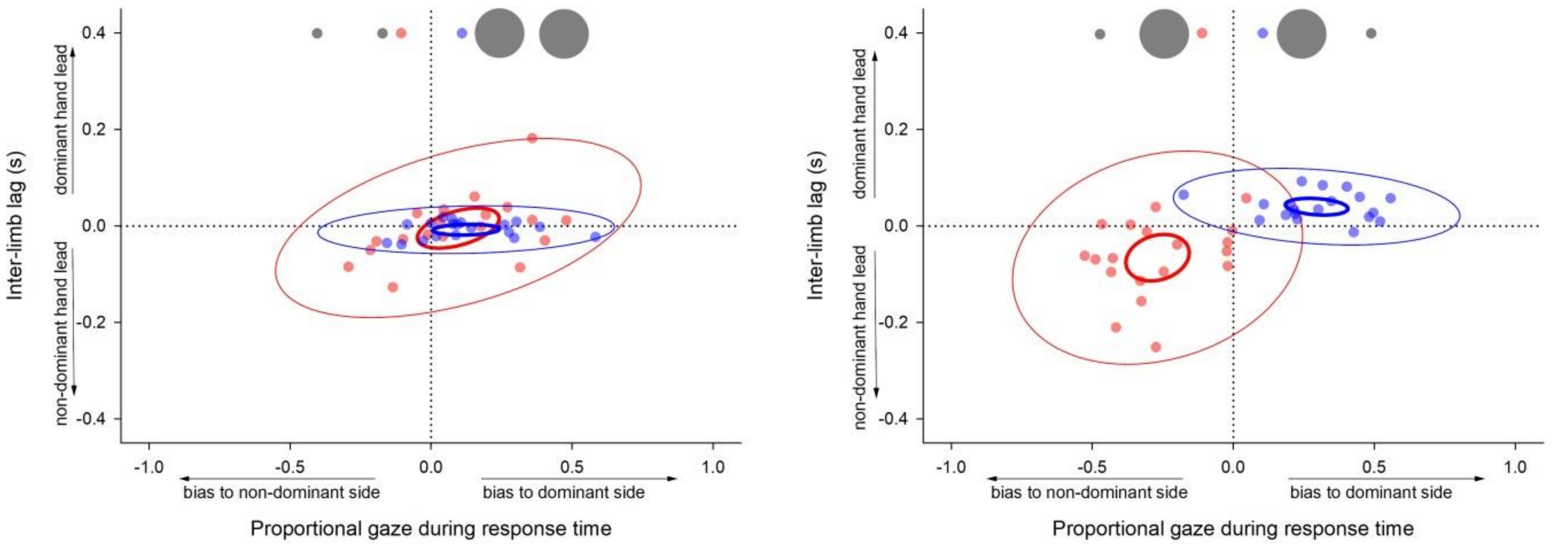


Figure 3.4 Scatterplots showing individual Inter-limb lag mean data as a function of proportional gaze bias during response time and inter-limb lag. Data are presented for both congruent (left panel) and incongruent (right panel) conditions and colour-coded for individual conditions. Ellipses denote confidence (thin line) and prediction (thick line) intervals.

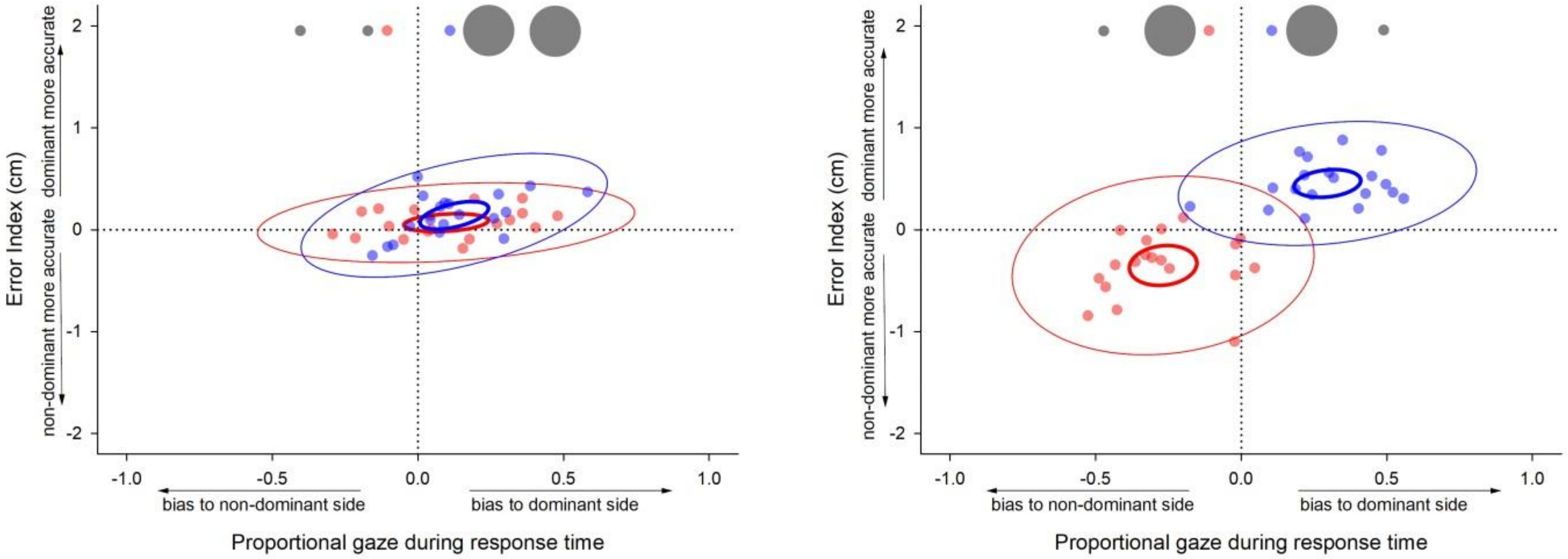


Figure 3.5 Scatterplots showing individual mean error data as a function of proportional gaze bias during response time and relative accuracy. Data are presented for both congruent (left panel) and incongruent (right panel) conditions and colour-coded for individual conditions. Ellipses denote confidence (thin line) and prediction (thick line) intervals.

Discussion

This study set out to investigate the visual control of bimanual aiming movements in young unimpaired participants. Participants made both unimanual and bimanual movements to targets which varied in size while limb and eye movements were measured. For bimanual movements, targets presented were either the same size (termed *congruent*) or were of different sizes (termed *incongruent*). The basic aiming task used, shared numerous similarities with previous studies of bimanual aiming and prehension, where kinematic data were reported in the absence of any eye movement data (Marteniuk et al., 1984, Corcos, 1984, Fowler et al., 1991, Castiello et al., 1993, Jackson et al., 1999, Bingham et al., 2008, Bruyn and Mason, 2009, Miller and Smyth, 2012, Hesse et al., 2010). Before considering the eye movement data presented here and relations with the limb movement data reported, kinematic data is discussed in relation to comparison with previous studies.

Basic kinematic findings and similarities to previous studies

Kinematic data generated by the task demonstrated some well-established features of unimanual and bimanual control. Firstly, unimanual movements to small targets were slower than those to large targets, the IoD reflected in line with Fitts' Law (Fitts, 1954). Bimanual movements were also slower than unimanual movements, reflecting the *cost* of performing two movements simultaneously. This cost was also evident for reaction time confirming recent work highlighting the impact of bimanual movements on movement preparation (Blinch et al., 2018). Where bimanual movements were to equally-sized targets (i.e. were *congruent*), Fitts' Law *held* with slower movements when the targets were small. Also consistent with previous studies, where bimanual movements were to differently-sized targets, Fitts' Law did not apply. Indeed, for these incongruent bimanual movements, while coupling between the limbs ensured that some measures (e.g. peak speed, response time) were comparable for movements to small and large targets, other measures (e.g. movement time, deceleration time) indicated faster movements for the *small* target. This provided the first indication in the study that some asynchrony was occurring for bimanual movements (see later). At this point, it is also worth noting that the only *hand dominance*-related finding was that the dominant limb was more accurate overall than the non-dominant limb; this is consistent with the accepted view that the dominant limb is superior in performing visually-guided movements (Goble and Brown, 2008a, Sainburg, 2002).

Signs of asynchrony

Although average movement data are helpful in order to make some broad comparisons with previous studies, it is important to recognise that these data can mask asynchrony occurring on a trial-by-trial basis (Bruyn and Mason, 2009, Miller and Smyth, 2012). In this experiment, measures of both signed (i.e. capturing left or right bias) and absolute asynchrony, derived from a trial-by-trial analysis revealed interesting findings. At movement onset and during the early stages of movement, tight synchrony between the limbs was apparent and was consistent with the preponderance of influential bimanual coordination literature emphasising coupling between the limbs (Kelso et al., 1979, Swinnen, 2002). However the asynchrony that emerged in the latter stages of movement and was captured at movement end appears to be driven by the varying visual requirements of the task largely in line with a number of more recent studies (Miller and Smyth, 2012, Bruyn and Mason, 2009, Bingham et al., 2008).

Importantly, while these previous studies have tended to highlight the influence of the overall visual demands of the task in increasing asynchrony, here it is seen that it is the relative demands placed on each limb that was most critical in maximising asynchrony. Accordingly, asynchrony was most pronounced in the incongruent conditions rather than the most demanding condition (i.e. *congruent small*). It appears that the relative demands of each target creates a competitive element typical of other visual attention tasks (Duncan et al., 1997) leading to prioritisation of the limb with the more demanding task with consequently greater asynchrony. Accuracy data were also supportive of this idea. For incongruent conditions, accuracy for small targets was comparable with that for unimanual movements (i.e. no noticeable *cost* of bimanual activity), while movement accuracy to the large target was most disrupted. In contrast, both targets bore the cost of bimanual movements more equally (see Fig. 3.1).

An initial consideration of eye movement data

Eye movement data during bimanual movements revealed that participants spent time looking towards each target for a given period of time on each trial and were therefore supportive of overt orienting being used to guide the movement of both limbs. When considering the proportion of time directing gaze to the dominant vs. non-dominant side, there was a tendency for more time to be spent directing vision towards the more difficult smaller target for incongruent trials, in a manner largely comparable with data reported by Riek et al. (2003).

Eye movement data were partially consistent with a previous report highlighting a greater tendency to make eye movements towards the dominant side during bimanual aiming tasks (Honda, 1982); e.g. there was a dominant side bias in the *congruent large* condition. This finding is consistent with the general view that the dominant limb is relatively more reliant on visual feedback for control (Goble and Brown, 2008a) and with research suggesting a dominant side attentional bias during bimanual tasks (Peters, 1981, Buckingham and Carey, 2009, Buckingham and Carey, 2014). However, a far more pronounced bias in overt orienting was observed during incongruent conditions. Here, regardless of the side (i.e. dominant or non-dominant), overt orienting was biased towards the more difficult (smaller) target.

Relations between eye movements, asynchrony and accuracy

This study provides new evidence relating to how different bimanual conditions lead to changes in where participants direct their vision during bimanual movements, and how these eye movements are associated not only with accuracy but also to the timing asynchronies that emerge between the limbs. Importantly, data here, for the first time show a clear relationship between overt orienting and asynchrony during the latter stages of bimanual aiming movements. Accordingly, the limb reaching the target first (i.e. the leading limb) was consistent with the side to which vision was mainly directed. For example, if the non-dominant hand touched the target first then eye movements were biased in the same direction, and vice-versa. By considering this relationship (i.e. between overt orienting and inter-limb asynchrony) on a trial-by-trial basis, a clear picture emerges of overt orienting in a given direction being associated with a corresponding limb lead. While less pronounced, these relations are further borne out by the tendency (at least for incongruent bimanual movements) for there to be greater target accuracy on the side where there is a visual bias and a limb lead. Importantly, here it was seen that increased asynchrony was not simply a function of difficulty. The condition with the highest index of difficulty was the bimanual congruent condition where both hands were aiming for the small (most difficult) targets. Rather, the greatest asynchrony and the largest visual bias occurred when bimanual movements were made to targets with different Iods.

The different competing demands of individual movements appear to drive greater desynchronization in bimanual control. It is proposed that this situation where bimanual coordination involves component unimanual movements that have distinct indices of difficulty drives competition in the visuo-motor system. The challenge for the control system is to resolve the individual requirements of these movements while optimising the temporal coordination of both movements. Hence, one could see this as a continuum of bimanual control; at one end of this continuum, bimanual movements are perfectly synchronous whereas at the other end, bimanual movements unfold serially. Factors contributing to the progressive desynchronization of bimanual movements appear to include (i) *differing (i.e. incongruent) movement requirements of the limbs*, (ii) the *level of* *visual guidance required*, (iii) *manual asymmetry (i.e. dominance) – though not in this study*, and presumably, (iv) *impairment*.

Other considerations

It is possible that the accuracy requirements of this study were not so exacting as previous studies requiring the of movement of styli (Riek et al., 2003) and cylindrical objects (Srinivasan and Martin, 2010) to the target locations. The more naturalistic pointing movements and more precise measuring of accuracy in the present study (i.e. error distance was measured in mm, rather than simply recording hit or miss) may account for some differences found. Moreover, unlike these two previous studies, we found no evidence of a *hover phase*, described as a period where one limb remains stationary close to the target until both limbs are aligned before finally touching the targets together (Riek et al., 2003, Srinivasan and Martin, 2010). Again, differences in task constraints are likely to account for these differences.

In this study, visual bias was represented by the relative amount of time participants spent looking left vs. right. While these data are informative, given the (sometimes) multiple saccades occurring during individual trials, it is important that future research explores the relationship between overt orienting and limb lead as bimanual movements unfold *within* a trial. It is possible that the leading limb switches multiple times within a discrete action (trial), determined by the sequence of related eye movements taking place.

In terms of attentional orienting, this study tracked the direction of eye movements and was therefore primarily concerned with *overt* attentional orienting. It is important to acknowledge that previous studies have explored the control of bimanual reaching movements while participants fixate their vision either centrally or on one particular target (Bruyn and Mason, 2009, Jackson et al., 2002a). In these studies, participants can only orient covertly and data suggest that the contribution of covert visual attention is not inconsiderable. For example, Bruyn and Mason (2009) showed that individuals accurately scale their grasp (a relative measure of accuracy) when performing bimanual reach to grasp movements to different-sized targets. This behaviour was similar whether participants were free to make eye movements or fixated their vision centrally between the two targets, suggesting good selective control using covert visual attention. However, as the acuity of visual information deteriorates rapidly with distance away from the point of foveation, it is not surprising that individuals select to make eye movements when performing bimanual movements in everyday life. Nevertheless, determining the relative contributions of *overt* vs *covert* visual orienting to the visual control of bimanual movements remains an area for future study. This issue was addressed explicitly in the following chapter (Chapter 4).

As noted above, limb asynchrony appears to increase as a function of greater competition between target/objects. In the present experiment, the size of targets was manipulated but greater competition could also be introduced by manipulating distance (e.g. Bruyn and Mason, 2009) and the degree of separation between targets (e.g. Srinivasan and Martin, 2010).

Finally, the visual control of bimanual movements is critical to normal everyday functioning and a major challenge for people who have impairments affecting their limb movements and/or vision. While previous studies have carefully inestigated bimanual reaching movements in a range of different disorders such as stroke (Jackson et al., 2000, Punt et al., 2005b, Punt et al., 2005a), Parkinson's Disease (Castiello and Bennett, 1997, Alberts et al., 1998) and spinal cord injury (Britten et al., 2018), we are not aware of any previous clinial studies that have investigated related visual control (i.e. eye movements) in these populations. Examining the visual control of bimanual movements in these populations, using approaches such as the one reported here would be informative and potentially allow coherent planning of rehabilitation strategies. This issue was addressed in Chapter 5 of this thesis.

Conclusion

In summary, this study provides further evidence of the complex and strategic manner by which humans control bimanual movements. It continues and strongly supports the emphasis that recent research has placed on the asynchronies that that can emerge as these movements unfold (Bruyn and Mason, 2009, Miller and Smyth, 2012, Srinivasan and Martin, 2010). Target characteristics modulated the relative difficulty of the component unimanual movements. Performing these movements concurrently appeared to set up an element of competition, with individual movements competing for visual resources. Furthermore, where this resulted in a visual bias to one side, the related limb showed a strong tendency to reach its target first leading to marked asynchrony between the limbs during the latter stages of movement. Data show how the visuo-motor system balances its apparent drive for synchrony in the planning and execution of bimanual movements with the need to visually guide the limbs to two different locations.

Chapter 4: Control of aiming movements using covert attention

Abstract

The study focuses on the role of covert attention in control of unimanual and bimanual upper limb movements. A novel aiming task was developed, where participants executed unimanual and bimanual reach movements to touch screen targets. Eye movements were controlled for using Electro-Oculography, whereby experimental trails that contained eye movements were excluded from analysis. Ten right-handed unimpaired individuals were included in the study.

Although kinematic analyses were in line with previous findings in literature and chapter 3, of particular interest were novel findings on accuracy, laterality and errant saccades. The results showed higher accuracy, and therefore a proprioceptive advantage for the non-dominant limb. Further to this, the majority of errant saccades were towards the dominant (right-hand side) in unimanual as well as bimanual conditions, suggesting a right-hand bias for visual resources. Finally, of note was the finding that participants were more accurate to bimanual targets compared to unimanual targets.

Findings reflect the fundamental differences in how movement is controlled and coordinated between the two limbs/ hemispheres; the left hand shows a proprioceptive advantage, and the right hand demands a greater share of the visual attention in a covert aiming task. Moreover, the weighted contribution of motor (proprioceptive) and covert

visual attention is biased towards the motor aspect during bimanual movements, resulting in superior accuracy than those of unimanual movements.

Introduction

Findings from Chapter 3 revealed that during bimanual movements to targets with equal distance, asynchrony between the two limbs arises as task demands require the visuomotor system to balance the drive to synchronise both limbs with the need to visually guide the limbs to two different target locations. In conjunction with previous studies Bruyn and Mason (2009), (Bingham et al., 2008, Srinivasan and Martin, 2010), limb asynchrony was modulated by task demands, as the two limbs compete for the shared resource of vision as bimanual movements unfolded. For incongruent conditions, there was a strong tendency for a visual bias towards the target side with the higher index of difficulty, as well as the relative limb leading towards the same target at movement end.

The findings from Chapter 3, summarised above, shows that visual attention shifts depending on the requirements of the bimanual task and in this previous study, eye movements provided the indicator of visual attention. However, visual attention may be either overt (measurable change in eye position) or covert (a shift in attention in the absence of an eye movement). Both *types of* attention are thought to play an important role in the control of bimanual movements (Diedrichsen et al., 2004, Bruyn and Mason, 2009, Srinivasan and Martin, 2010). Examining eye movement reaction times during unimanual reaching movements, Fisk and Goodale (1985) showed the efficiency of the visuomotor system, in that it optimally distributes overt visual attention to the limbs to ensure accurate reaching movements, with results showing shorter eye movement reaction times for movements towards the ipsilateral side compared to the contralateral side, as well eye movements being temporally scaled to limb movements. Although humans naturally visually fixate on the targets or objects they are manipulating Hayhoe and Ballard (2005) showed that reaching movements can also be completed without the necessity for eye movements (i.e. using covert attention), for example, turning a light switch on whilst walking into a room. From a phylogenic viewpoint, covert shifts in attention serve are advantageous as they allow the individual to attend to objects within the visual field without the typical processing cost of a motor response (Diedrichsen et al., 2006, Carrasco, 2011). Influential research over 40 years ago (Posner, 1980, Posner et al., 1978) provided compelling evidence of a covert visual attention; findings showed that even in the absence of gaze shifts, subjects respond faster to a target if they are preceded by a cue on the same side prior to their appearance, demonstrating visual attention can be biased without the need for eye movements. Today, the importance of covert visual attention in understanding visual perception is more widely understood (Findlay and Gilchrist, 2003), although its related contribution to movement control has been explored far less.

Previous studies have examined the associated costs of executing bimanual movements using covert attention, by fixing vision during reaching movements, although this has never previously involved formal monitoring of eye movements, or what might be considered *errant saccades* during such a task. Jackson et al. (2002a) examined the effect of gaze direction on unimanual and bimanual reaches, where subjects were asked to fixate on only one target object during the task, i.e. some reaches were executed using covert attention. Results showed that when subjects reached to two separate targets, there was no temporal lag between the two limbs. Furthermore, the key difference between the fixed vision and free vision conditions during bimanual movements was that grip aperture was calculated separately for each limb relative to the gaze information available. For instance, the foveated target side limb showed a narrower grip aperture compared to the peripheral viewed target side limb, which showed a wider grip aperture, suggesting that the restrictions to vision do not disrupt coupling of the reach movements but the grasp component is independently scaled as a function of the quality of visual input available. Similar findings are reported by Bruyn and Mason (2009), who considered the role of covert attention in bimanual reach to grasp movements where visual attention was controlled by fixation of vision to either a central point, or right or left side onto the target object. Of interest was the finding that visual feedback available to the visuomotor system influenced the fine motor control of the limbs, for instance, in the fixate-left and fixate-right conditions, maximum grip aperture for the non-fixated hand was larger across movement conditions, whereas in the natural vision and fixate-centre conditions the maximum grip aperture was comparable between the two limbs, despite equal object size for all conditions. The results indicate that temporally coupled bimanual movements can be performed in the absence of overt attention, and that adjustments are made in limb control to account for the changes in visual resources available.

Further research by Miller and Smyth (2012) focused on temporal coupling between the limbs in the absence of vision, where participants made reaching bimanual movements with and without visual feedback of the limbs. Findings showed absolute temporal lag between limbs was observed when visual feedback was available; however, in the absence of vision, the limbs were coupled at movement end. This seemingly unintuitive finding was attributed to the lack of inter-limb crosstalk and noise that arises when vision is used to control bimanual movements; and a common, temporally synchronous goal is adopted for both limbs in the absence of vision. Findings from Miller and Smyth (2012) suggest that temporally coupled bimanual movements can be executed in the absence of visual feedback where task parameters allow. Although overt or covert shifts in attention were not formally measured, there is a possibility that the occlusion of vision led to synchrony between the limbs, as the temporal cost associated with using overt attention to guide both limbs onto their respective targets is absent. Bingham et al. (2008) conducted a study into components of bimanual prehension movements and found that the movement onset and time to peak velocity were comparable for the limbs, with temporal coupling between limbs observed. However, decoupling between the limbs was observed when the visual demands of the task, such as the grasping area of the target being too small or the objects being very wide, constrained movement synchrony in the latter component of movement. Findings from this study that temporally synchronous bimanual movements may be the default mode of movement, and the requirements for visual information in the later stages, which is usually the deceleration phase, ultimately yields temporal asynchrony between the limbs.

Results from the aforementioned studies suggest that temporal coupling between the limbs may be enhanced using covert rather than overt attention. In agreement with previously mentioned studies and as results from Chapter 3 showed, synchrony between the limbs during reaching movements is modulated by the attentional demands of the task; temporal asynchrony between the two limbs was observed in the incongruent conditions where the smaller target was ascribed a greater share of visual resources as well as the relative limb lead towards it. Further empirical evidence of efficiency in 'online' covert control of bimanual movements comes from a reach to point study by Diedrichsen et al. (2004), who found that when bimanual reaching movements trajectory were displaced by perturbations, the visuomotor system was able to correct the movements with high accuracy without overt eye movements, suggesting that covert attention was sufficient to make adjustments to reaching movements. Previous research (Diedrichsen et al., 2004, Miller and Smyth, 2012) shows that movement kinematics such as peak speed, time to peak speed and movement time of both limbs are comparable under covert control of bimanual movements. Thus, one would expect that deceleration time, the phase where the visual guidance of the limbs takes place (Riek et al., 2003), as also observed in findings from Chapter 3, would be shorter when covert attention is used to control bimanual movements rather than overt attention as presence of eye movements would be associated with a temporal cost.

The temporal cost of bimanual movements using overt attention is well documented in previous literature (Jackson et al., 1999, Hesse et al., 2010, Riek et al., 2003) as well as in Chapter 3; whereby movement planning and execution time is longer for bimanual movements compared to unimanual movements. Results from Riek et al. (2003's) findings of a ‘hover phase’ during the deceleration phase as well as the findings that the cost of bimanual movements may be modulated largely by the visual guidance of the limbs onto the targets, with eye movements being an indicator of overt attentional shifts. Although not yet formally reported in previous studies, one would expect that for limb movements using covert attention, the bimanual cost of movement would be significantly reduced as the movement planning stage will not require planning of overt shifts in gaze as it will remain centrally fixated, further to this, the temporal cost associated with online control of each limb competing for the shared resource of vision to foveate onto the targets will also be diminished.

Results from Chapter 3 showed the dominant limb was more accurate across unimanual and bimanual conditions during visually guided reach movements. Empirical support comes from research by Roy and Elliott (1986), who showed a preferred-hand advantage in task accuracy and temporal performance in reaching movements. Furthermore, in a condition where vision of the limbs and the target was occluded after movement initiation; the preferred-hand was more accurate, suggesting that the dominant hand is more adept at utilisation of covert as well as overt shifts in attention. Further study by Roy et al. (1989) also showed this preferred-hand advantage in a third condition where the lights are turned off (i.e. under covert attention, where no visual feedback is available) 10 seconds prior to movement initiation. Findings from (Roy et al., 1989, Roy and Elliott, 1986) and bias in eye movements towards the preferred hand in Chapter 3 suggest that the dominant hand is more reliant on visual feedback than the non-dominant hand.

Previous research by Honda (1982) considered the monitoring of dominant and non-dominant limbs for bimanual reaching movements using EOG, and found that greater amount of time is spent gazing towards the dominant arm during a reaching movement, which in turn results in improved temporal performance compared to the non-dominant arm. Furthermore, where the experimental task required subjects to make eye movements to only one side, results showed that the preferred arm was more reliant on vision than the non-preferred, as the absence of vision affected the preferred arm more than the non-preferred arm. This study offers a suggestion that there may be a difference in how the dominant and non-dominant limbs make use of overt and covert visual feedback available.

The dominant limb may be more reliant on vision for guidance onto targets in conditions where the visuomotor system is not constrained in shifts in overt attention throughout movement, as results from Chapter 3 support this notion, as results showed higher accuracy for the dominant limb in comparison to the non-dominant limb, with the dominant limb also allocated a greater share of visual resources during bimanual movements. However, where the visuomotor system is constrained so that only covert shifts in attention are permissible, thus, each target cannot be foveated onto individually and only peripheral visual input is available, one would expect the dominant limbs advantage to wane during bimanual movements.

The visuomotor system controls upper limb movements using overt and covert shifts in attention. Surprisingly few studies have explored the visual control of reaching movements using covert attention, where eye movements are fixed throughout the movement. Chapter 3 showed that necessity for overt shifts in attention can lead to small asynchronies during bimanual movements, that are modulated largely and visual demands of the smaller target in incongruent conditions. Of interest in the current study is how the visuomotor system will control and coordinate bimanual movements under covert control, and whether the inherent drive for inter-limb synchrony will remain unperturbed by the visual demands of the task. For reaching movements using covert attention, the hypotheses contend that limb accuracy and inter-limb synchrony will be modulated by how the visuomotor system balances the drive to synchronise the limbs with the attentional demands of the congruent and incongruent targets. Based on previous studies and theoretical concepts raised in this introduction, one would expect,

(i) The limbs to be closer in temporal synchrony compared to overt attention

(ii) The dominant limb to have an accuracy advantage over the non-dominant limb

(iii) The cost of bimanual movements to be diminished

Methods

Participants

Ten right-handed individuals (three females) aged between 20 and 23 years old participated in the study as unpaid volunteers. All participants had normal vision and had no known neurological or musculoskeletal disorders. Handedness was confirmed using the Edinburgh Handedness Inventory (Oldfield, 1971).

Apparatus, Procedure, Dependent variables and Statistical analysis

A majority of the Apparatus, Procedure, Dependent variables used and statistical analysis conducted was as detailed in Chapter 2 and has been omitted from this section to avoid repetition. A few changes made to the protocol and analyses are detailed below.

Changes in experimental protocol

Gaze fixation

The experimental protocol was changed so that Electrooculography (EOG) was used as a method of controlling for eye movement. Instead of using EOG to measure eye movements, any saccades were recorded using EOG and the relative trials where eye movements were detected were subsequently excluded from kinematic analysis. Fig 4.2 presents a trial with an Errant Saccade, which would be excluded from kinematic analysis. Fig 4.1 illustrates the threshold signal value of EOG signal of ±.01mV; the red dotted line the cut off for leftward eye movements, and the blue dotted line for rightwards eye movements. A small margin was reserved to allow for changes in the Electroculogram signal due to minor head movements. A positive value for the EOG signal represented a right sided eye movement, and negative value represents a left sided saccade.

Differing from the experiments in Chapters 3 and 5, where the fixation cross disappeared after targets appeared on screen, to affix vision centrally, a fixation cross (black, 4cm x 4cm) was presented in the centre of the screen throughout the trial.

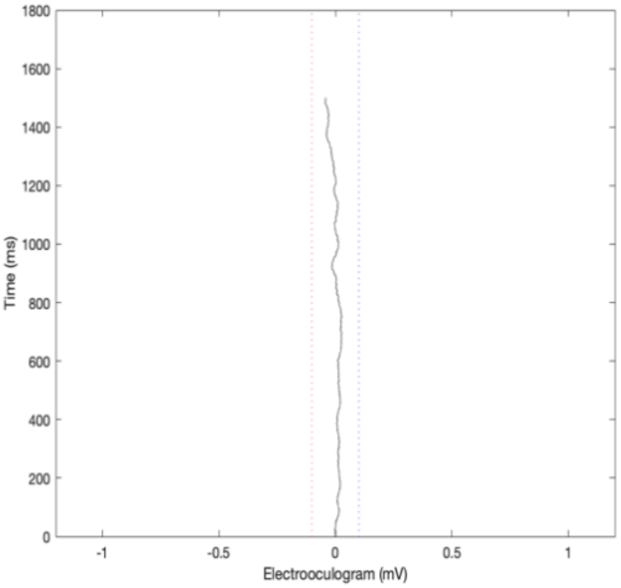


Figure 4.1 Illustration of EOG signal in a gaze fixed trial

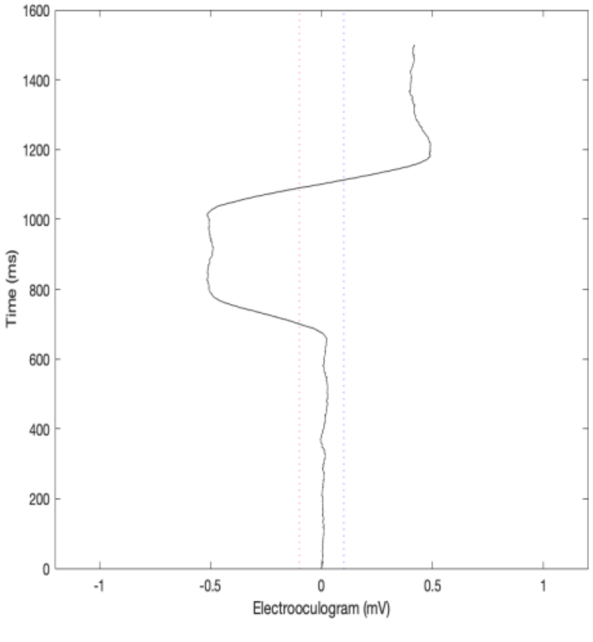


Figure 4.2 Illustration of EOG signal in an Errant Saccade trial

Additional Statistical analysis

The statistical analysis was as detailed in Chapter 2.

An additional dependent variable of *Errant Saccades* was included to support meeting experimental objectives. Here, the data from trials that were excluded from kinematic analysis due to eye movements was analysed.

A 2 x 2 analysis of variance (ANOVA) with repeated measures was conducted; for unimanual movements factors (levels) were *Saccade Side* (left vs. right) and *Target size* (small vs. large). For bimanual movements a 2x2x2 repeated measures ANOVA was conducted, where factors (levels) were *Congruence* (congruent vs. incongruent), *Left size* (small vs. large) and *Saccade Side* (left vs. right).

Ethical statement

The project was reviewed and approved by the University of Birmingham's Science, Technology, Engineering and Mathematics Ethical Review Committee. Participants provided written informed consent prior to taking part.

Dependant variables

Limb movement measures

Reaction time (RT): time (ms) from target onset (touchscreen) movement onset (first frame when the speed exceeds 50mm/s).

Movement time (MT): time (ms) from movement onset to movement end (touchscreen).

Response time (ResT): time (ms) from target onset to movement end i.e. (i) + (ii).

Acceleration time (AT): time (ms) from movement onset to time that peak speed (see below) is reached.

Peak speed (PS): the highest speed (mm/s) reached during the limb's movement towards the target.

Deceleration time (DT): time (ms) from the frame peak speed reached to movement end.

Target acquisition error (TE): the distance (mm) from centre of target circle to the touch point.

Coupling relations between the limbs

Absolute and relative inter-limb synchrony was measured at Movement onset; Time of peak speed; Movement end in milliseconds (ms).

Results

Limb movements

Reaction time (RT)

The ANOVA revealed significant main effect of Size (F (1, 9) =8.278, p=0.018); reaction times were faster for movements to large targets (mean= 395ms) compared with those to small targets (mean = 408ms). Reaction times were statistically comparable for unimanual (mean = 412ms), bimanual congruent (mean= 394ms) movements and bimanual incongruent (mean= 398ms) movements (p=0.339). An interaction between condition and size (F(2,18 = 5.528; p=0.013) showed that in unimanual conditions, reaction times were faster for movements to large targets (mean= 392ms) compared with those to small targets (mean = 431ms) (F(1,9 = 23.665; p=0.001), whilst they were comparable for *bimanual congruent* (F(1,9 = 0.515; p=0.491) and *bimanual incongruent* (F(1,9 = 0.905; p=0.366) conditions.

Acceleration time (AT)

No significant main effects or interactions were found for Condition (F (2, 18) =0.938, p=0.410), Side (F (1, 9) =0.036, p=0.853) or Size (F (1, 9) =0.205, p=0.662) variables; acceleration time was comparable for unimanual (mean= 162ms), bimanual congruent (mean= 158 ms) and bimanual incongruent (mean=166ms) conditions.

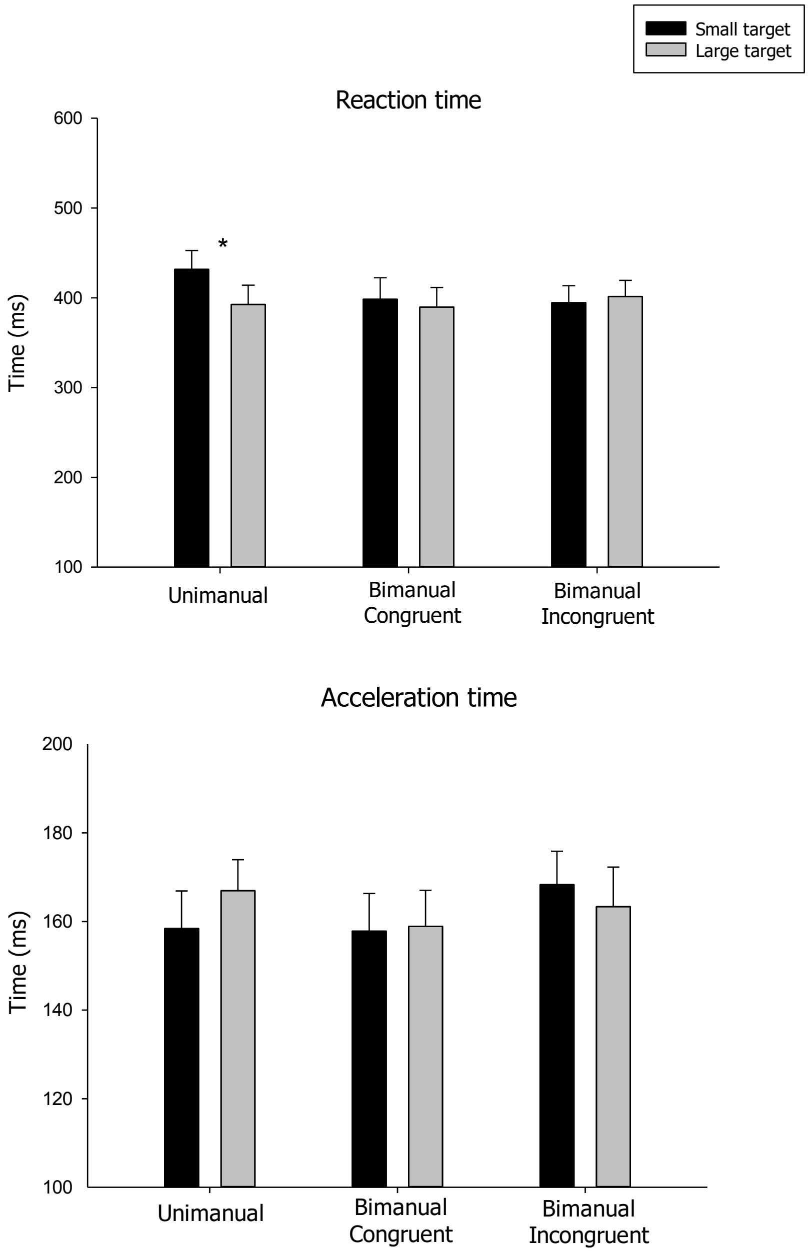


Figure 4.3 Mean RT and AT as a function of target size for each of the three conditions. Error bars denote the standard error of the mean. Asterisks denote statistical significance.

Peak speed (PS)

No significant main effects or interactions were found for Condition (F (2,18) =0.585, p=0.567), Side (F (1, 9) =0.043, p=0.840) or Size (F (1, 9) =2.704, p=0.135) variables; Peak

Speed was comparable for unimanual (mean= 1288 mm/s), bimanual congruent (mean= 1293 mm/s) and bimanual incongruent (mean= 1317 mm/s) conditions.

Movement time (MT)

A Condition x Size interaction (F (2, 18) =5.866, p=0.011) was observed. MTs were faster to large targets (mean= 457 ms) compared with small targets (mean = 522 ms) under unimanual (F (1,9) = 6.131, p=0.035) and bimanual congruent (small mean = 606 ms, large mean = 500 ms; F (1,9)= 9.057, p=0.015) conditions, whereas under bimanual incongruent conditions, MTs were comparable between large targets (mean = 567ms) and small targets (mean = 551ms; F(1,9)= 2.459, p=0.151).

Across all conditions, there was a significant main effect of Condition (F (2, 18) =6.679, p=0.007); MTs for unimanual movements (mean= 490ms) were significantly faster than bimanual incongruent MTs but comparable to bimanual congruent MTs (p=0.118); MTs for bimanual congruent (mean= 553ms) and incongruent (mean = 559 ms) conditions were comparable (p=1.00). Movement Time was significantly affected by Size (F (1, 9) =11.024, p=0.009); MTs for large targets (mean = 560ms) were faster than those for small targets (mean = 508ms).

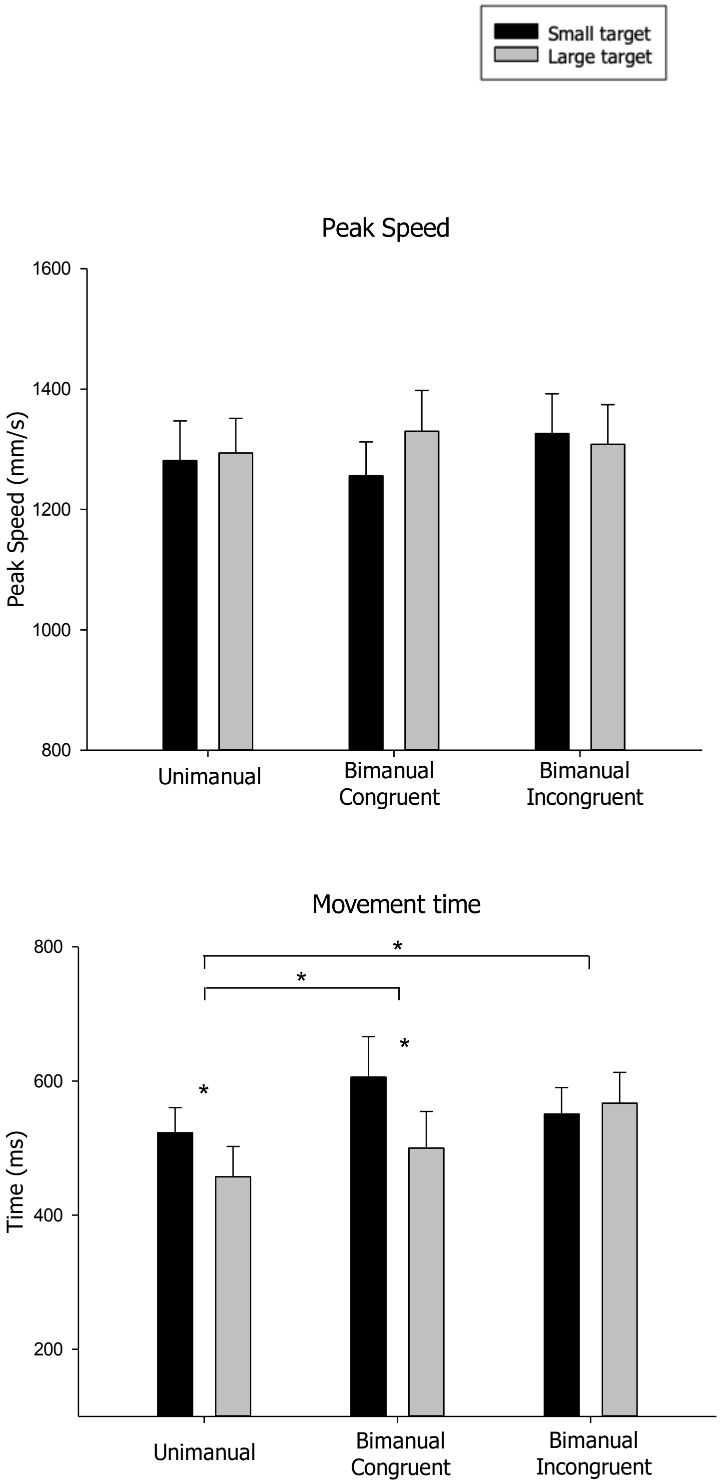


Figure 4.4 Mean PS and mean MT as a function of target size for each of the three conditions. Error bars denote the standard error of the mean. Asterisks denote statistical significance.

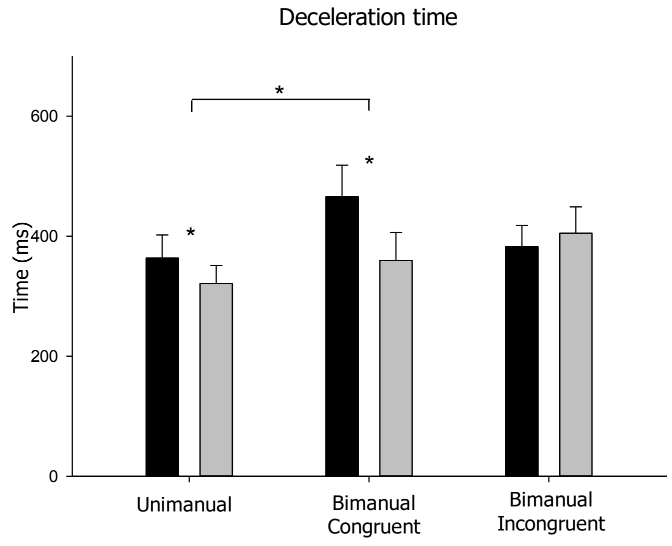
Deceleration time **(DT)**

A Condition x Size interaction (F (2, 18) = 13.799, p=0.001) revealed a different pattern of data for size depending on the condition. While DTs were longer for small targets compared with large target in the unimanual (small mean = 363 ms, large mean = 321 ms; F (1,9) = 10.351, p = 0.011) and bimanual congruent conditions (small mean = 466 ms, large mean = 359ms; F (1,9) = 18.742, p=0.002). For bimanual incongruent conditions, however; DT was comparable between large (mean= 405ms) and to smaller targets (mean= 382ms) p=0.060) The ANOVA revealed a significant main effect of Condition (F (2, 18) = 6.749, p=0.007); pairwise comparisons revealed unimanual movements (mean = 342ms) to have a shorter DT than bimanual congruent (mean= 412ms, p = 0.044) but not bimanual incongruent (mean 394ms, p=0.074). The two bimanual conditions produced comparable DTs (p=0.978). The side of target did not have a significant effect on the deceleration time observed (p=0.314). Additionally, there was a significant main effect of Size (F (1, 9) = 18.692, p=0.002) with a tendency for DTs to be longer for small targets.

Response time (ResT)

A Condition x Size interaction (F (2, 18) = 18.711, p=0.001) revealed slower ResT to small targets (mean = 957ms) than those to large targets (mean =880ms) for the unimanual conditions (F (1, 9) = 45.712, p=0.001). For bimanual congruent conditions, responses were faster to large targets (small mean = 1017 ms, large mean = 908 ms; F (1, 9) = 18.958, p=0.002), whereas for bimanual incongruent conditions, response times were faster to the small target (small mean = 941 ms, large mean = 970 ms, F (1, 9) = 9.482, p=0.013).

A significant main effect of Size was found; responses to large targets (mean = 919ms) were faster than those to small targets (971ms) (F (1, 9) = 28.405, p=0.001). No effect of the side of target was found; response times were comparable between the right and left hand (p=0.936).



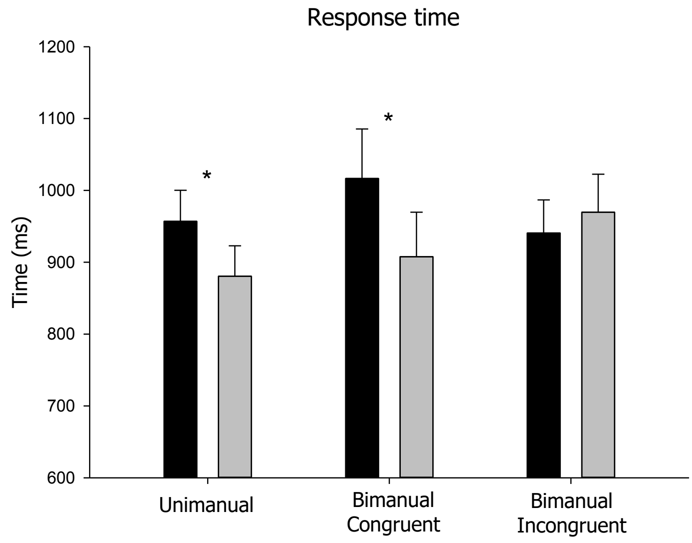


Figure 4.5 Mean DT and ResT as a function of size for each of the three conditions. Error bars denote the standard error of the mean. Asterisks denote statistical significance.

Target Error

Across all conditions, the left (non-dominant) (mean = 0.762 cm) limb was more accurate than the right (dominant) limb (mean = 0.903 cm). (F(1,9)= 14.922, p = 0.004). Additionally, accuracy was greater for bimanual congruent (mean = 7.76 cm) and bimanual incongruent (mean = 7.96 cm) than unimanual movements (mean = 9.26cm F(2, 18 = 11.185), p = 0.001.

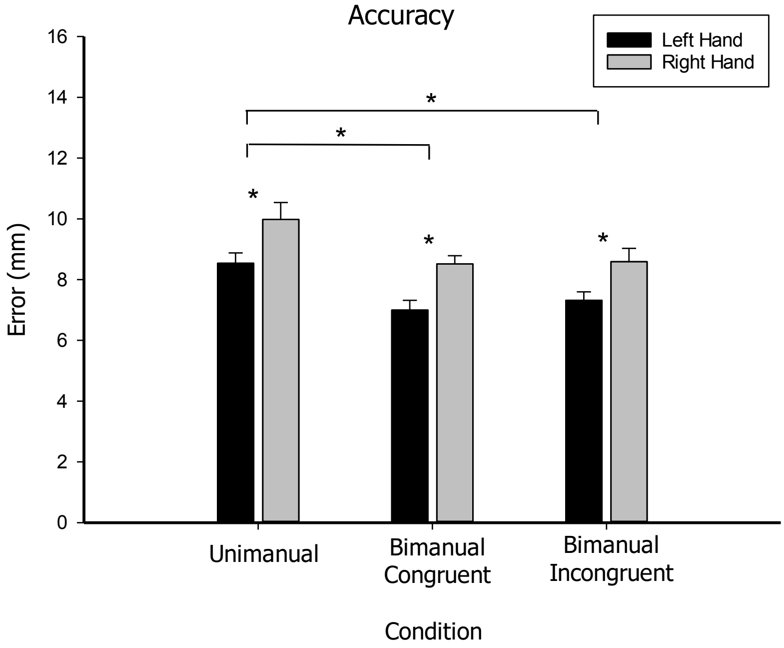


Figure 4.6 Mean Target Error as a function of size for each of the three conditions. Error bars denote the standard error of the mean. Asterisks denote statistical significance.

Limb synchrony

Similar to the previous chapter, for bimanual movements we examined synchrony at various time points via a series of 2x2x2 ANOVAs with repeated measures; factors (levels) were Congruence (congruent vs. incongruent), Left size (small vs. large) and Bias (initial number vs. it's additive inverse). The reason for the latter factor was to provide an indication of whether the asynchrony for the signed lag significantly deviated from the ‘opposite’ mean for directional gaze. A main effect of Bias would indicate that the directional lag is significantly different compared to the inverse. Relative directional signed synchrony as well as absolute temporal difference between the limbs at movement landmarks is presented.

Movement onset synchrony

At movement onset, the right and left limb moved in temporal synchrony relative to each other, with signed mean movement onset times for each limb being within 5ms of each other (p=0.341). There were no other significant main effects of the target size, congruence, or condition. Data in Figure 4.7 illustrates this temporal synchrony by condition. In terms of absolute lag between the two limbs, data showed a 20ms difference at movement onset with main effects of congruence and target size (p= > 0.05).

Time to Peak Speed synchrony

At TTPS, both limbs remained temporally coupled (p=0.124) ; see figure 4.7. Results of the ANOVA showed a slight, statistically insignificant, lead for the left hand of 10ms with no main effects or interactions The ANOVA revealed a 32 ms absolute temporal lag between the two limbs, with no main effect of the target size or congruence of condition (p= > 0.05).

Movement end synchrony

At movement end, the limbs were temporally synchronous, with the overall mean across all conditions showing a lag of 6 ms in the direction of the left limb (p= 0.494); no other significant main effects or interactions observed. Figure 4.7 illustrates the inter-limb relations across all conditions, showing the limbs to be temporally coupled until movement end. The ANOVA revealed a larger temporal difference of 45 ms between the two limbs at movement end, with no main effect of the target size or congruence of condition ($p= > 0.05$).

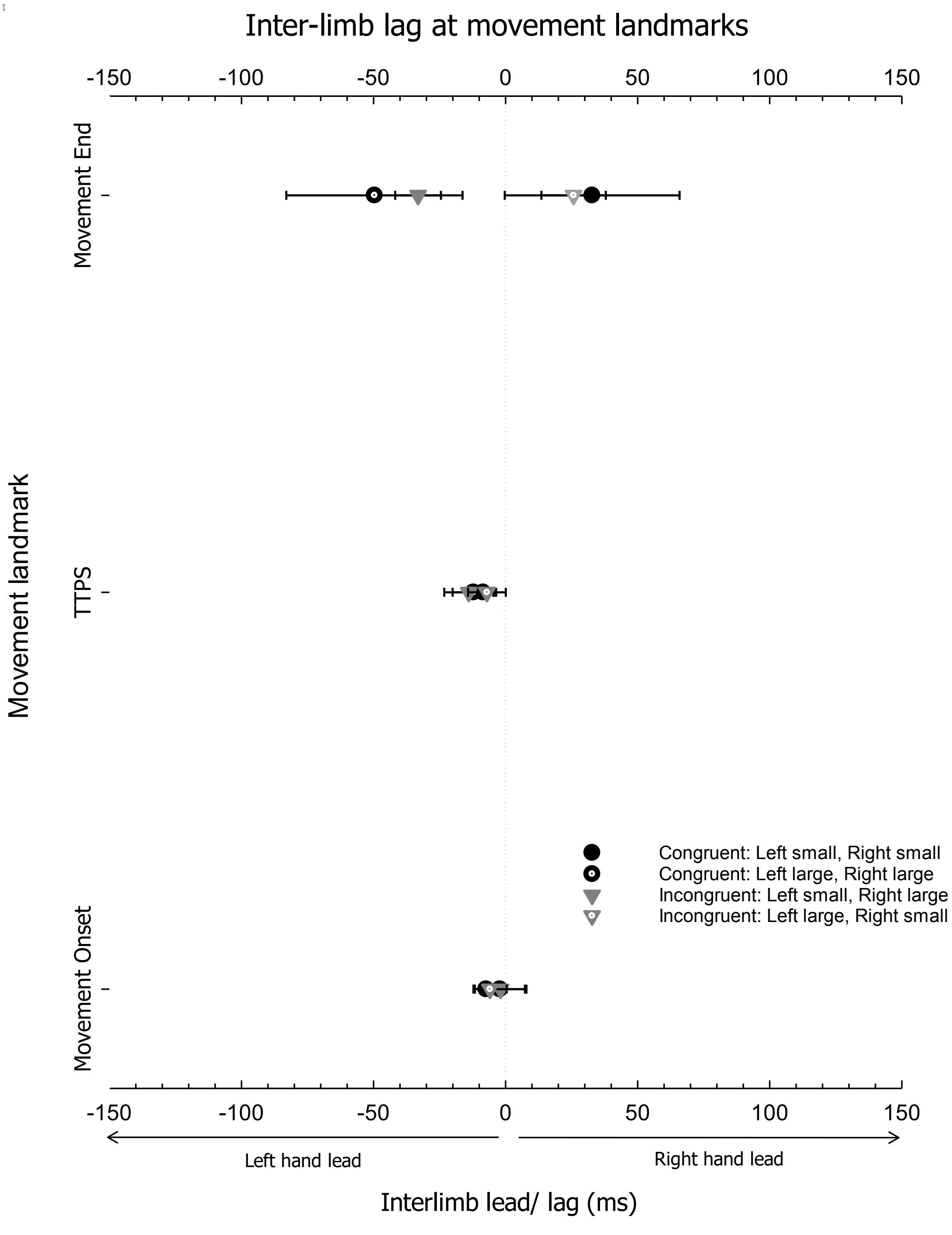


Figure 4.7 Inter-limb asynchrony (lead/lag) shown as a function of congruence and phase of movement landmark. Error bars denote the standard error of the mean. Negative values indicate a left hand lead; positive values indicate a right hand lead

Errant saccades

An errant saccade was defined as an eye movement which occurred within the trial whilst the participant was reaching towards the target.

A total of 180 out of 800 trials were removed from kinematic analysis due to errant saccades; these were then further analysed by the direction of eye movement and the condition they occurred in. As there were 10 trials in each condition, means are reported as percentages.

For unimanual conditions, 61 trails out of 400 (15.3%) contained errant saccades. The results of the ANOVA on errant saccades during unimanual movements of these revealed no significant main effects. However, an interaction between Hand Side x Target Size (F (1,9) = 6.639; p= 0.030) was present; as figure 4.8 suggests, the interaction appeared to show a greater percentage of errant saccades rightwards for right handed targets, particularly for small sized targets compared to large sized targets, however, this difference was not significant after Bonferroni corrections (p=0.058).

For bimanual conditions, 119 trails out of 400 (29.8%) contained errant saccades. The ANOVA revealed a main effect of Saccade direction (F (1,9) = 6.351; p=0.033); across all bimanual conditions, participants were significantly more likely to make errant saccades in the rightwards direction (mean= 23.3%) compared to the leftwards direction (mean = 6.5%). There were no other main effects or interactions to report.

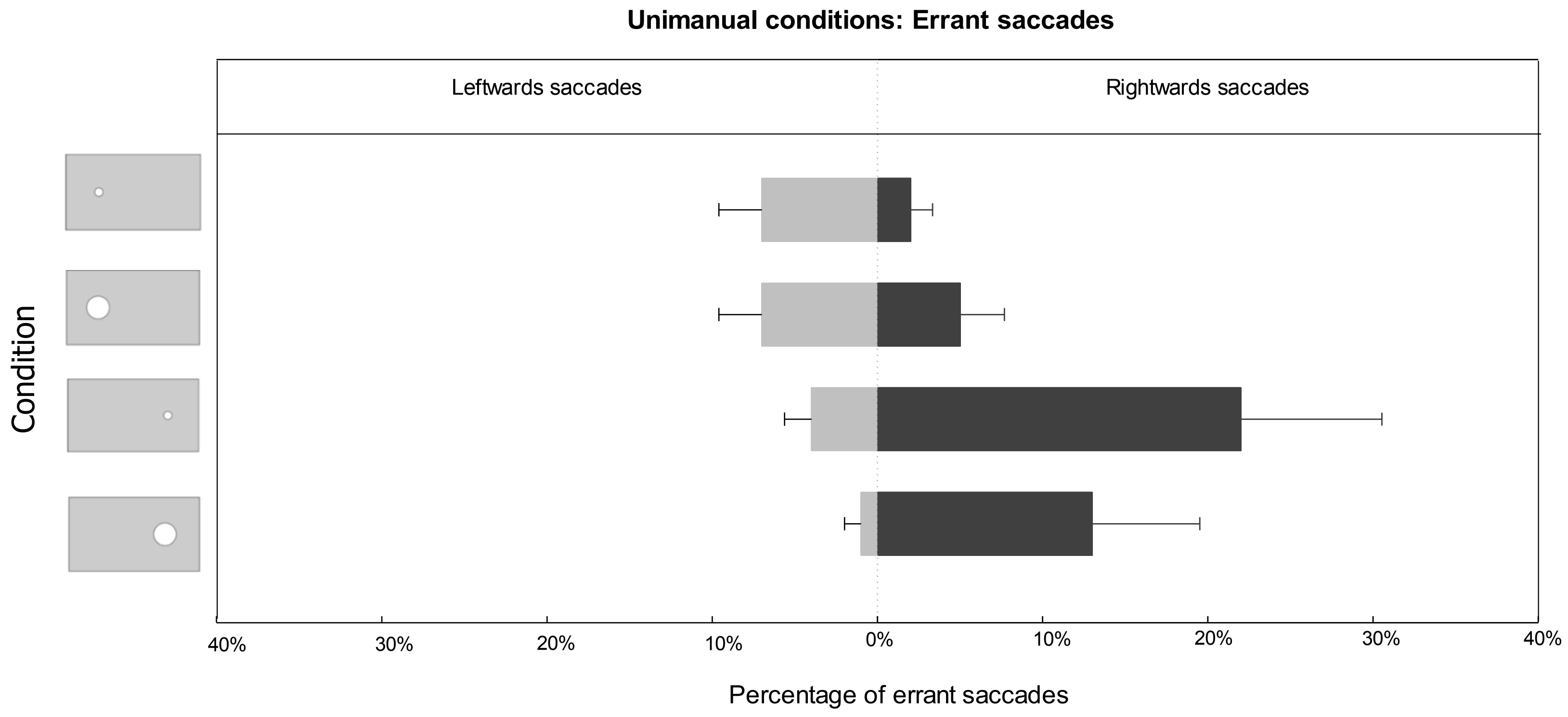


Figure 4.8 Percentage of errant saccades for unimanual conditions in each direction. Leftwards saccades are assigned a negative value, and rightwards saccades a positive value.

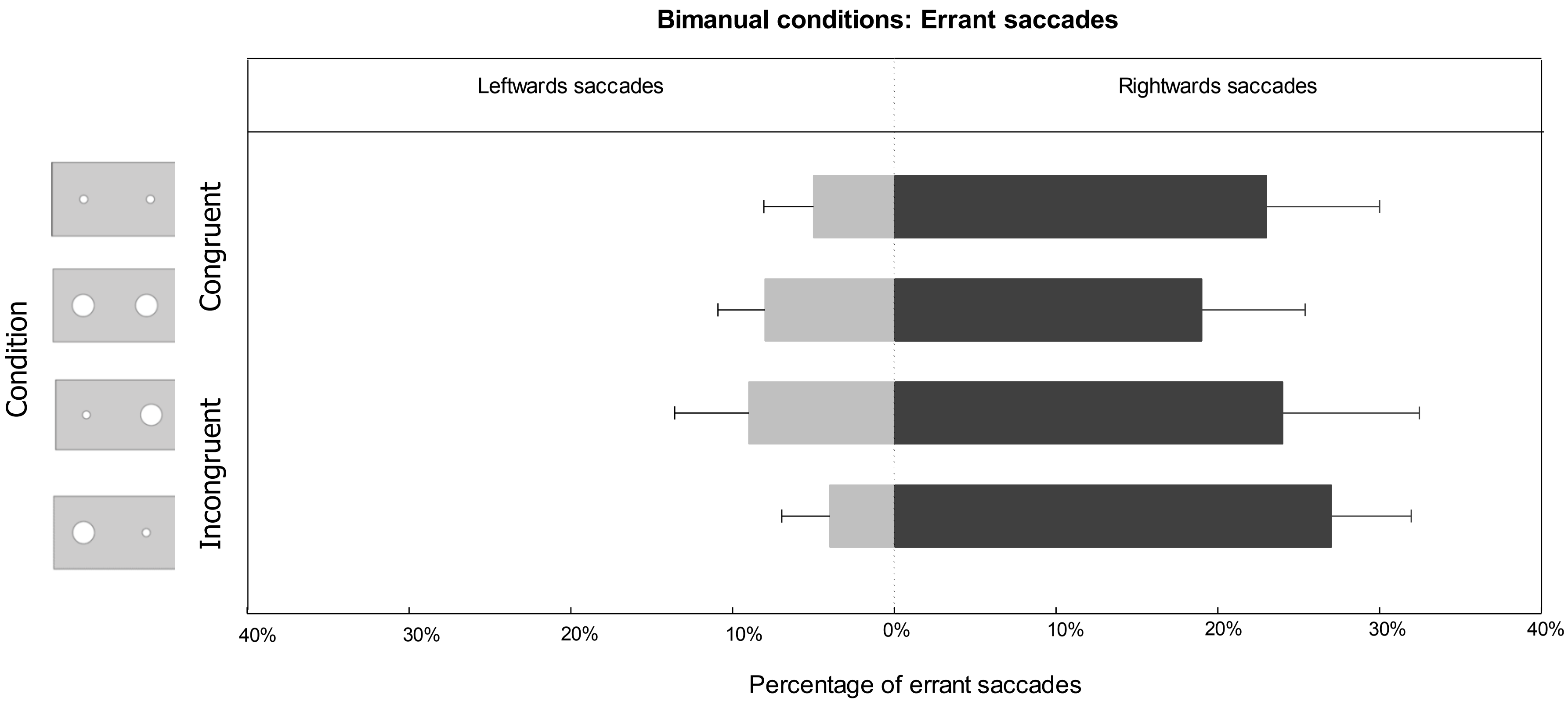


Figure 4.9 Percentage of errant saccades for bimanual conditions in each direction. Leftwards saccades are assigned a negative value, and rightwards saccades a positive value.

Discussion

The current study aimed to examine the visual control of bimanual movements when individuals are constrained to only using covert visual attention. Under normal circumstances, both overt and covert visual attention plays a role in visual control of bimanual reaching movements, however, this study aimed to limit participants to using the latter. Based on previous studies (Jackson et al., 2002a, Miller and Smyth, 2012, Bruyn and Mason, 2009), it was hypothesised that visual constraints would have little effect on task completion, however, the pattern of data would vary considerably from that when using overt visual attention. The hypothesis contended that during reaches to targets; (i) the limbs would be closer in temporal synchrony compared to overt attention given that that visual requirements drive the between-limb asynchrony; (ii) the dominant limb would have an accuracy advantage over the non-dominant limb; (iii) the cost of bimanual movements to be diminished.

Results revealed important differences in how upper limbs are controlled using covert attention where although visual feedback is available to the visuomotor system, it is relatively low in acuity, in comparison to overt control of limb movements. As previous research (Binsted et al., 2001) found, gaze fixation on targets through explicit eye movements (and shifts in covert attention) were not necessary to provide the visuomotor system with sufficient information about the target location in order to compete reach-to-target movements. As hypothesised, movements were less accurate under covert visual control, as the fixed gaze assured targets were not foveated on, and thus resulted in reduced accuracy; whereas under overt control participants were more accurate in reaching to targets, with a difference of over 3 cm over all (Covert control TE mean =0.832cm vs. Overt control TE mean= 0.521cm). Further to the accuracy findings, the predictions on faster kinematics of movement under covert control were also confirmed. Data showed faster movement time for limbs controlled using covert attention, due to the lack of temporal cost that is associated with shifts in gaze towards targets for visual guidance of the limbs. Fitts' Law (1954), the speed-accuracy trade-off was less constrained by the visual demands of the task under covert control, whereby although the speed of movements was faster under covert control (Covert control MT mean =534ms vs Overt control MT mean = 781ms), and was inversely proportional to the accuracy of movement achieved (Covert control TE mean vs. Overt control TE mean= 0.521cm), which can be attributed to the poorer acuity of visual feedback.

As well as having faster movement times, bimanual movements were also more coupled together under covert control compared to overt control of movements; (see Fig 3.2 in comparison to Fig 4.7). However, analysis revealed that although the limbs were more tightly temporally coupled for movements under covert control, lags in movement were still modulated by task conditions. For instance, results showed that during incongruent trials, although gaze was fixated centrally throughout the movement, the limb moving to the smaller target tended to be reaching it first, thereby resulting in a small asynchrony in favour of the smaller target. In similarity to Chapter 3, where changes in gaze were also followed towards the limbs, the findings reveal that covert visual attention is modulated by task parameters, where the target with the relatively higher index of difficulty modulates limb movement in incongruent conditions during bimanual reaching movements. In a manner largely comparable with data reported by Bingham et al. (2008) the movement requirements of each limb modulated coupling between the two limbs; motor attention was biased to one side during bimanual, which lead to temporal asynchrony between the limbs.

Kinematic results from the experiment revealed further interesting findings. Under overt attentional control of movements, a majority of kinematic measures showed a *Condition* effect, driven by the change in performance from unimanual to bimanual movements. However, for movements under covert attentional control of movement, this was not the case; most variables showed comparable performance between unimanual and bimanual movements. Overall movement response time showed a cost for bimanual response times, however, the difference was far less pronounced that that seen when movements were controlled with overt visual attention. These data suggest that the cost of bimanual movements is driven largely by the nature of the visual requirements.

Nevertheless, there were also notable similarities in data from this experiment when compared with those from Chapter 3. For example, as was seen in the previous chapter and in other previous studies (Jackson et al., 2002a, Bingham et al., 2008, Bruyn and Mason, 2009), participants scaled movement times for unimanual and bimanual congruent conditions in line with Fitts' Law (Fitts, 1954); movement times were shorter for larger targets that had a lower index of difficulty than smaller targets which had a higher index of difficulty. However, similarly to movement under overt visual control, this was not the case for bimanual incongruent conditions, where coupling ensured that movement times were comparable for simultaneous movements to small and large targets. In this study, it appears that sensory information available via covert visual attention was sufficient to allow scaling, albeit less pronounced for covert than overt visual attention as observed in findings from Chapter 3.

In addition to these predicted findings, the experiment also revealed some unanticipated and intriguing findings. Each of these will be now taken in turn.

Left limb movements were more accurate than right hand movements

In contrast to chapter 3 and some previous literature (Sherwood, 2014, Zuoza et al., 2009, Bruttini et al., 2016), where the dominant limb was more accurate, the results from the current experiment showed that the non-dominant left limb was more accurate. While previous evidence (Honda, 1982, Roy and Elliott, 1986, Roy et al., 1989, Goble and Brown, 2008a) has highlighted how the dominant limb has a relatively higher reliance on visual feedback with regards to its typically enhanced performance, it was not expected that changing the nature of visual feedback in this experiment would have such a concentrated effect. Furthermore, complementary evidence from research by and Barthelemy and Boulinguez (2001) and Goble and Brown (2008a) suggests the non-dominant limb may be more adept in using proprioceptive feedback. In the absence of overt shifts in gaze, the sensimotor system is more reliant on additional sensory input. Research by Sober and Sabes (2005) offers explanation; as visual feedback is contrained, the weighting of sensory guidance during the task is biased towards proprioceptive input (Sarlegna and Sainburg, 2009, Blouin et al., 2014), which the left limb is more adept at utilising.

Bimanual movements were more accurate than unimanual movement

Perhaps even more intriguingly, data from this experiment revealed that bimanual movements were more accurate than unimanual movements. This was particularly surprising, as visual guidance under overt attention control (Chapter 3) and other studies (Jackson et al., 1999, Corcos, 1984, Blinch et al., 2018) showed, part of the *cost* implications of bimanual movements is that they are slower and less accurate than unimanual movement. The findings cannot be attributed to a simple speed-accuracy trade-off in performing movements (Fitts, 1954, Carlton, 1981b, Carlton, 1981a). On the contrary, response times (RT) under covert attentional control failed to show the typical cost of bimanual movements, being comparable across all conditions. This counter-intuitive finding can be explained by the aforementioned theory of weighting of sensory information, which can be applied to concurrent bimanual movements. Typically, the planning and execution of reaching movements requires the integration of visual and proprioceptive signals to ensure optimal performance (Sarlegna and Sainburg, 2009); where sensory signals are weighted depending on movement requirements of the task (Blouin et al., 2014, Sarlegna and Sainburg, 2009). In the case of unconstrained visually-guided unimanual movements, the target is foveated, providing reliable sensory (visual) guidance of the movement; i.e. vision is very strongly weighted. As previously discussed, unconstrained bimanual movements to separate targets (as in Chap 3) create a relative challenge for motor control as two targets cannot be foveated simultaneously. As a result, optimal control is achieved by foveating each target independently and making eye movements as the bimanual movements unfold. However, in this case, as there are periods of time where a reaching movement is not under direct visual guidance, therefore the weighting of proprioception may be greater.

For unimanual movements, Reaction time (RT) is slower for smaller targets (see Fig 4.3); suggesting that attempt to use the relatively poorer visual input. Furthermore, for bimanual movements, visual information becomes even less reliable as the visuomotor system needs to simultaneously gather positional information from two different locations simultaneously. In the case of bimanual movements, it is speculated that the relative contribution of (the more reliable) proprioceptive input is weighted more heavily, thereby resulting in superior accuracy for bimanual movements in comparison to unimanual movements. Of course, this explanation is speculative, but appears to be able to account for the data observed and studies investigating these issues a priori are indicated.

Errant saccades showed a strong bias to the dominant side

Finally, it was surprising to observe both the number of errant saccades, (15% of unimanual trials and 30% of all bimanual trials) and their marked right-sided bias (75% of all errant saccades). While previous studies have investigated bimanual movements while attempting to fix vision (Bruyn and Mason, 2009, Jackson et al., 1999), none of these formally measured eye movements. For the current experiment, EOG offers the optimal approach in gaze fixation, as it allowed researchers to sensitively and accurately ensure fixation was maintained; and where it wasn't; it was possible to objectively measure the errant saccades. Though unpredicted, the right-sided bias appears to provide converging evidence for some of the explanatory remarks made above. Firstly, with regards to the superior performance of the non-dominant (left) upper limb discussed above, these data appear to be consistent with the dominant limb's relative reliance on visual guidance. Indeed, the data strongly suggest that there is a clear asymmetry in the ability to inhibit saccades during reaching tasks. Research by Sainburg (2002), (Sainburg and Kalakanis, 2000) suggest that the two limbs are mediated by separate internal models, with distinct neural control mechanisms employed for dominant and non-dominant arm movements; with Goble and Brown (2008a) suggesting that the right limb is more adept at utilising visual feedback, therefore requiring comparatively more visual feedback to make limb movements. Secondly, the observation adds significantly to previous findings suggesting attention is biased to the dominant side during bimanual tasks (Peters, 1981, Buckingham et al., 2011, Buckingham and Carey, 2009, Honda, 1982). However, even given some of these previous findings, the extent of the bias observed in this study seems remarkable and emphasis the marked differences in laterality there appears to be in human motor function.

Conclusion

This chapter has revealed insights into the how the visuomotor system controls and coordinates unimanual and bimanual reaching movements under covert control, the absence of overt shifts in gaze. Participants were able to perform bimanual aiming movements using covert attention, albeit at a cost of poorer accuracy in comparison to movements under overt attentional control. The absence of overt shifts in gaze appeared to modulate the greatly diminished cost of performing bimanual movements, which also corresponded with more tightly coupled bimanual movements. Yet, the visual requirements in incongruent conditions modulated the small asynchronies that were observed, similarly to findings in Chapter 3. Nevertheless, even with reduced visual acuity, participants were able to use covert visual attention to scale movements to small and large targets in a manner consistent with movements under overt visual control as reported in Chapter 3. Finally, a series of unexpected findings reinforced previous suggestions relating to asymmetry between the upper limbs in their use of sensory guidance and attentional biases during bimanual coordination.

Comparison between overt and covert attention

A series of ANOVA were carried out to formally compare the role of overt and covert attention in reaching movements. Dependant variables of accuracy, reaction time, response time, peak speed, as well as interlimb lag at movement onset, peak speed and movement end were selected for comparison; results are presented and discussed in turn below.

Accuracy

Overall, participants were more accurate when guiding limbs under overt attention (mean= 0.516cm) compared to covert attention (mean= 0.865cm); (F(1,27)= 47.661, p = 0.001).

Reaction time

The reaction time was faster when guiding limbs under covert attention (mean= 401ms) compared to overt attention (mean= 463ms); (F(1,27)= 5.120, p = 0.032).

Response time

Participants response time was significantly faster under covert attentional control (mean= 945ms) compared to overt attentional control (mean= 1250ms); (F(1,27)= 11.019, p = 0.003).

Peak speed

Although the peak speed was appeared to be faster for reaching movements under overt attentional control (mean=1199mm/s) compared to covert attentional control (mean = 1299mm/s); the ANOVA showed no main effect of Group (F(1,27)= 1.132, p = 0.297).

Lags

Movement onset synchrony

At movement onset, the right and left limb moved in temporal synchrony relative to each other for both Overt attention (mean lag= 27ms) and Covert attention (mean lag= 35ms) (F(1,27)= 2.076, p = 0.161).

Time to Peak Speed synchrony

At TTPS, both limbs remained temporally coupled (F(1,27)= 2.982, p = 0.096) under both Overt attentional (mean lag= 41ms) and Covert attentional (mean lag= 29ms) groups.

Movement end synchrony

Although the interlimb lag appeared to be larger for reaching movements under overt attentional control (mean lag = 92ms) compared to covert attentional control (mean lag= 57ms); the ANOVA showed no main effect of Group (F(1,27)= 2.379, p = 0.135).

Discussion of findings

Findings agreed with the conclusions derived from Chapter 4, where although participants were able to perform bimanual aiming movements using covert attention, this came at a cost of poorer accuracy in comparison to movements under overt attentional control. The absence of overt shifts in gaze appeared to modulate the greatly diminished cost of performing bimanual movements, as demonstrated by the faster reaction time of movements under covert control. The faster reaction time under covert visual attention suggests a shorter planning of limb movements. The longer response time for movements under covert control suggests that requirements to visually guide eyes onto targets modulated response time, which also resulted in greater accuracy. Interestingly, despite the observed differences between movements under covert and overt control, interlimb synchrony as well as peak speed was comparable under both groups, suggesting that despite the absence eye saccades, the visuomotor system is able to complete reaching movements with relative acuity and accuracy.

Chapter 5: The visual control of bimanual movements in stroke survivors with mild hemiparesis

Abstract

Bimanual coordination is characterised by the coupling of temporal and spatial components of movement, even where the requirements of the individual movements vary. Data in this thesis have shown that unimpaired participants respond to the competing demands of individual movements by directing greater visual resources towards the side with the more difficult task. Here, eleven chronic stroke survivors with mild hemiparesis and no cognitive problems, along with ten older adults control participants made unimanual and bimanual reaching movements to targets of different sizes presented on a touchscreen. Limb and eye movements were measured. Given performance in unimpaired individuals, we predicted that stroke participants would prioritise the hemiparetic side (i.e. the more difficult task) in comparison to the unaffected limb, directing visual resources to it and modifying control of the contralateral limb to optimise coupling.

As expected, stroke participants were slower and less accurate in performing unimanual movements with their hemiparetic limb compared to the unaffected limb. However, data from bimanual conditions were surprising. While limbs were largely coupled at movement onset, the hemiparetic limb lagged substantially behind the contralateral limb at movement end, indeed, the cost (in terms of speed and accuracy) of bimanual movements for stroke participants appeared to be borne entirely by the hemiparetic limb; the unimpaired limb proceeded as if unconstrained in any way. Also contrary to our prediction,

eye movements were not biased to the impaired side but showed comparable patterns to those shown by the control group despite the marked differences in limb movements. These data highlight the marked challenges that bimanual movements pose to stroke survivors with mild hemiparesis. They may also expose an implicit lack of full awareness for hemiparesis (anosognosia); stroke participants appeared to plan and execute movements in a manner that did not account for their motor deficit.

Introduction

Chapter 3 showed that despite competing demands of component unimanual movements (both internal and external), participants' largely maintained synchrony between the limbs although some small (< 100 ms) asynchronies emerged at movement end. Even where the index-of-difficulty for component unimanual movements varied markedly, the visuomotor system sought to balance the drive for synchrony with the need to visually control the two limbs during bimanual movements. Inter-limb coupling was achieved by modifying the use of visual resources and the kinematics of each limb; for example, during incongruent bimanual movements, participants modified the kinematics of both limbs in order to optimise coupling while mainly directing visual resources towards the more difficult target. Based on these findings in unimpaired individuals, it was speculated what the impact of impairment would be on the control of bimanual limb movements; gaze throughout bimanual movement would be biased towards the affected side to compensate for the impairment of the hemiparetic limb, so that inter-limb coupling is optimised by the visuomotor system. Hemiparesis following stroke affects motor performance of an upper limb with implications for functional hand and arm movements (Wade et al., 1983). In this chapter, data are reported from 11 stroke survivors and 10 age-matched controls on the same task as used in Chapter 3. The experiment aimed to explore the impact of limb impairment (hemiparesis) on the visual control of bimanual movements.

To provide a background for this chapter examining the visual control of bimanual movements in stroke survivors with mild hemiparesis, this introduction will discuss, (i) the relevance and importance of bimanual coordination following stroke, (ii) previous studies examining bimanual coordination following stroke (iii) the importance of vision for the control of bimanual reaching movements, and (iv) the rationale for the study and the related hypotheses in light of mentioned theoretical considerations.

The relevance and importance of bimanual coordination following stroke

Collaboration between the two hands is necessary for a majority of daily activities (Kilbreath and Heard, 2005, Maes et al., 2017), with the motor system striving to couple the movements temporally (Sherwood, 1991) while optimising the accuracy and efficiency of coordination (Franz, 2003). However, for such coordination to be maintained in the presence of an impaired limb, the process of coordinating bimanual activities must adapt. Following stroke, limb function is affected in a majority of the population, with 77%-80% of stroke survivors reporting some degree of upper limb motor impairment (Lawrence et al., 2001b). The severity is variable with some individuals experiencing relatively mild problems with control while others may experience total paralysis (Ward et al., 2006). A majority of everyday functional tasks incorporate movements that require the ability to reach and grasp, with motor and sensory deficits in arm function likely to cause significant difficulties in performing these with negative consequences for the quality of life of stroke survivors (Winstein et al., 2016).

For carrying out activities of daily living (Mahoney and Barthel, 1965), some functional activities may be achievable in stroke survivors without necessarily using both limbs. For example, an individual may select to use their unimpaired limb to make a series of movements to complete the task goal such as opening a cupboard door followed by reaching for an object using the same limb. Alternatively, one may compensate for the limb impairment by employing a movement plan that uses another part of the body to contribute to the task instead of the impaired limb, for example, opening a jar by holding it between the knees and using the unimpaired limb to unscrew lid. However, the optimal performance of many functional activities requires bimanual movements to be performed in a coordinated manner (Kilbreath and Heard, 2005). For example, cutting pieces of food using a knife and fork requires precise temporal and spatial relations between the limbs to ensure one hands holds the fork and food steady whilst the other hand is used to cut through it. In this case, a failure to coordinate temporal as well as spatial elements of the activity would result in task incompletion.

Hemiparetic stroke presents a challenge to the motor system in coordinating bimanual movements, and this is known to adversely affect functional reaching movements(Wu et al., 2008) and thus can have a significant impact on activities of ADLs outcome (Hellström et al., 2003). Moreover, research by Haaland et al. (2012) suggests that a stroke survivor's ability to couple their upper limb movements together is not simply related to motor impairment of the upper limb, and can serve as a predictor of functional ability following stroke; findings showed that higher scores on an adapted version of the ADL scale were associated with greater use of temporally coupled upper limb in chronic stroke patients with mild to moderate hemiparesis.

Previous studies examining bimanual coordination following stroke

Existing theories propose that the upper limbs move synchronously in a single functional unit (Turvey, 1977), and thus bimanual movements would require a longer processing time (Kelso et al., 1979). In a prehension task, Jackson et al. (1999) found that bimanual reaching movements where both limbs were in temporal synchrony had longer movement times and lower peak velocities than unimanual reaches. This performance difference that emerged between unimanual and bimanual movement seems to be the 'bimanual cost' that is required to ensure the two bimanual movements are temporally synchronous has been observed in earlier chapters, similar research studies (Srinivasan and Martin, 2010, Punt et al., 2005a) and also in stroke survivors with mild hemiparesis (Rose and Winstein, 2005), suggesting that the visuomotor system seeks to maintain bimanual coordination (temporal synchrony) between the limbs despite the limb impairment caused by brain injury.

Early work on inter-limb coordination in stroke patients was conducted by (Cohn, 1951), who studied pronation-supination movements and observed that the visuomotor system pursued temporal synchronisation between the impaired and the unimpaired limb during simultaneous movement. In an elbow flexion task, a simple movement task which does not involve a process of response selection that requires movement preplanning, (Dickstein et al., 1993) found that stroke survivors' impaired limb showed slower movement time compared to the unaffected limb for unimanual movements; interestingly, for bimanual movements, movement time increased significantly for both limbs for the stroke survivors, with the unaffected limb slowing down so that the two limbs are temporally coupled at movement end, with results suggesting that the temporal cost of bimanual movements is shared across the two limbs rather than an effect of hemiparesis itself.

For stroke survivors, the visuomotor system has to contend with reduced motor capability of the paretic limb as well as the temporal processing cost of performing bimanual movements compared to unimanual movements. The planning and execution of movements of both limbs has to be balanced with the 'drive to synchronise' limbs during bimanual movements, although both limbs have markedly different capabilities. Rose and Winstein (2005) showed that a longer planning time was required for bimanual movements compared to unimanual movements in stroke survivors; however, despite this bimanual cost, over 80% of bimanual trials were initiated and terminated simultaneously, with the visuomotor system adapting to maintain movement synchrony. Similar findings are reported by Kantak et al. (2016), where stroke survivors synchronised bimanual movements by slowing down their unaffected limb to accommodate the hemiparetic limb during the reaching phase of movement, suggesting that the motor system drives to synchronise bimanual movements whilst accommodating for the impaired limb.

The importance of vision in control of bimanual reaching movements

For functional movement completion in stroke survivors with limbs of dissimilar movement capabilities, sensory information regarding the position and motion of the hemiparetic limb is considered to play a vital role (Perenin and Jeannerod, 1978). Paretic limb movements are observed to be less smooth and have longer overall movement time than movements of the unimpaired limb (Trombly, 1993), with the deceleration phase of movement particularly slower as it is the phase where visual feedback is utilised to guide the limb towards the target. Furthermore, in comparison to the unimpaired limb, the paretic limb appears to require a greater share of visual resources during unimanual reaching movements compared to the unimpaired limb as it is weaker and slower (Krakauer and Carmichael, 2017) in comparison. Meadmore et al. (2018b) studied oculomotor control of unimanual reaching movements in stroke survivors and observed more visual saccades (i.e. greater requirement of visual resources) towards the impaired limb side during reach movements, with the impaired limb being less accurate and less likely to complete a reaching movement towards a visual target. Similar findings that suggest that the impaired limb is more reliant on visual resources for limb movement and daily life function are reported by Singh et al. (2018). On examining limb movements and saccades and their implications on performance in functional tasks using the Stroke Impact Scale, Singh et al. (2018) found that an increased number of saccades were made by stroke survivors when using their impaired limb compared to the control group in a unimanual movement task; as well as a decrease in reaching speed and smoothness, stroke survivors also had difficulty in performing functional tasks although the impaired limb had a greater share of visual resources.

In terms of daily living and function, Jeannerod et al. (1984) observed that a stroke survivor with hemianesthesia was able to use her hand for various functions of daily living provided that she could control limb movements visually; which highlights the necessity for vision in control of limb movement and the challenge faced by the visuo-motor system in that the two limbs cannot be fixated on simultaneously. During a symmetrical bimanual movement, where only one limb can be visually focused on at a given movement, one would predict that the hemiparetic limb, due to its poorer motor control, would require a greater proportion of visual guidance in comparison to unaffected limb. Results from Chapter 3 & Chapter 4 consider this competition for visual resources in an unimpaired population, where visual resources are modulated by the difficulty of the experiment condition and bimanual targets; for instance, vision is biased towards the smaller (more difficult) target side in incongruent conditions, as it has the highest index of difficulty (Chapter 3). In stroke survivors, one would expect the bimanual task conditions to place a greater strain on the hemiparetic limb to modulate vision, as the reduced motor capability of the hemiparetic limb will make the index of difficulty higher in comparison to the unaffected limb. Consequently, one would expect the hemiparetic deficit to be the modulating factor for vision rather than the targets' index of difficulty.

Rose and Winstein (2005) show temporal synchrony is maintained at movement initiation and termination for bimanual movements, with the longer deceleration phase being the corrective movement phase for bimanual movements, where the unaffected limb slows down to synchronise with the hemiparetic limb. However, some single case studies in stroke survivors with impairments report movement asynchrony at movement end during bimanual prehension movements. Research by Punt et al. (2005a) in a patient with motor neglect showed that although the limbs were coupled at movement onset, temporal coupling was not observed at movement end when reaching to separate objects. Similar findings are reported by Jackson et al. (2000), who found that a stroke survivor with dense hemianesthesia was able to complete comparable unimanual movements with the affected and unaffected limb yet showed marked impairment in her ability to execute bimanual movements although the limbs were coupled at movement onset. Temporal coupling at movement onset suggests that the motor plan for coupling is intact, however, as the movement unfolds temporal asynchrony increases. This breakdown in coupling in individuals with neurological impairments has been attributed to attentional biases towards the unaffected limb (Punt et al., 2005a) and in hemianesthesia, to the lack of proprioceptive cues forcing reliance on visual cues (Jackson et al., 2000). The aforementioned studies did not explicitly consider the role of vision during bimanual movements; doing so would provide more insight into the control and coordination of the limbs.

Rationale and hypotheses in light of mentioned theoretical considerations

Bimanual coordination remains a relatively neglected field of research in human motor control (Obhi, 2004), and understanding the mechanisms of bimanual coordination of the limbs has theoretical as well as clinical implications. For instance, clinical implications of research have applications in upper limb stroke rehabilitation, where the gap in theoretical understanding translates to lack of clear guidelines in upper limb rehabilitation literature following stroke and is an issue highlighted by therapists when treating patients with hemiparesis following stroke (Pomeroy and Tallis, 2002). For example, conflicting evidence and advice is present in upper limb rehabilitation following stroke induced hemiparesis; between Bimanual Movement Therapy (BMT) and Constraint Induced Movement Therapy (CIMT) . BMT advocates for movement of the impaired and unimpaired limb concurrently to make sure of the internal mechanisms of bimanual control to aid rehabilitation, whereas CIMT contents that constraint of the unimpaired limb would encourage more usage and therefore stimulate faster rehabilitation of the impaired limb. To date, no study has monitored visual control of bimanual movements in stroke survivors, investigation of visual control would shed light on the some of the complexities involved in the coordination and control of simultaneous bimanual limb movements. For individuals with hemiparesis, one would predict the impaired limb to require an unequal share of visual resources to successfully complete a bimanual reaching movement.

Following stroke, aside from the cost of bimanual movements, the visuomotor system faces the challenge of maintaining a balance between the drive for synchrony, the unequal demands of the limbs for visual resources as well as unequal contribution of the paretic limbs in planning and making bimanual movements. Cooperative interaction of the two limbs is involved in a majority of activities of daily living (Beets et al., 2015), many of which include reaching movements and present a challenge for stroke survivors; very few studies to date have explored inter-limb coordination in bimanual reaching in stroke survivors, and no study to date has considered study of visual control of reaching movements and the coordination between the limbs in chronic stroke patients. With reference to the aforementioned literature and our experimental design, the hypothesis contends that during reaching movements:

(i) Stroke survivors' impaired limb will be slower and less accurate compared to control participants during unimanual movements

(ii) Stroke survivors will allocate a greater share of visual resources towards the control of the hemiparetic limb during bimanual movements compared to older adult controls

(iii) Stroke survivors will slow their unimpaired limb in order to optimise temporal coupling during bimanual movements

Methods

Participants

Control group – Age-matched participants

10 right-handed participants with an age range from 71 to 82 were recruited from the Birmingham Elders voluntary participation mailing list. These participants reported to be in general good health and were free from any neurological impairment; participants with

any age-related illnesses (such as diabetes/ cardiac problems), were not excluded as long as their ability to complete the task was not affected by their condition.

Stroke affected participants

Participants were recruited from list of stroke patients who had previously been participants in the university and had opted in to be contacted for further studies. Further participants were recruited from the Life After Stroke Centre, Bromsgrove, Birmingham. The group included male and female participants with both left and right sided hemiparetic limbs, with an age range from 51 to 80 years old.

Inclusion and exclusion criteria

The primary inclusion criterion was for the participants to have previously had a stroke; however, the experiment also required a minimum range of movement from participants. Therefore, the exclusion criteria were stroke survivors who were not able to carry out the following set of instructions mimicking the experimental conditions:

- Lift your affected arm to shoulder level
- Straighten the fingers on your hemiparetic arm to point towards a target
- Make a pointing movement with your arm outstretched (as in Fig 2.6, Chapter 2, pg. 39)

Stroke survivors who had upper limb range of motion enough to complete the above instructions were invited to take part in the study.

During the initial screening, four potential participants were unable to accomplish such movements reliably due to lack of manual dexterity from the severity of hemiparesis and were excluded from further experimentation.

Apparatus, Procedure, Dependent variables and Statistical analysis

A majority of the Apparatus, Procedure, Dependent variables used and statistical analysis conducted was as detailed in Chapter 2 and has been omitted from this section to avoid repetition. A few changes made to the protocol and analyses are detailed below.

Changes in experimental protocol

To accommodate for the expected limb slower movements in stroke survivors and older adults controls, the experiment design was altered in that the targets appeared on screen for 7 seconds before disappearing; this ensured participants with limb impairment had sufficient time to make reaching movements towards the targets.

Additional protocol: impairment assessments

The following assessments for impairment in stroke survivors were conducted in addition to the protocol detailed in Chapter 2. Assessment scores and other characteristics of participants are summarised in Table 5.1.

Barthel activities of daily living

The Barthel scale or Barthel ADL index is an ordinal scale used to measure performance in activities of daily living (ADL). Each performance item is rated on this scale with a given number of points assigned to each level or ranking. Using variables describing ADL, this allowed researchers to gain an insight into the functional mobility of each participant.

Mini Mental State Examination

The Mini-Mental State Examination (*MMSE*) was developed in 1975 as a brief test for the quantitative assessment of cognitive impairment in adults. It has since been widely used by physicians throughout the world. As the MMSE is more sensitive in detecting cognitive impairment than the use of informal questioning or overall impression of a patient's orientation, it allowed us to accurately screen for cognitive impairment.

Star cancellation task

The Star Cancellation Test is a screening tool that was developed to detect the presence of unilateral spatial neglect (USN) in the near extra personal space in patients with stroke (Wilson, Cockburn, and Halligan, 1987).

Suitability requirements are that participants must be able to hold a pencil to complete the test (the presence of apraxia may impair this ability); and must be able to visually discriminate between distractor items such as the words and big stars, and the small stars that are to be cancelled.

Posner task

The Posner Cueing Task is a neuropsychological test often used to assess attention. The test allowed us to screen for attentional shift or eye movement impairment in participants.

Modified Ashworth

The Modified Ashworth Scale is considered the primary clinical measure of muscle spasticity in patients with neurological conditions. This allowed us to screen for major spasticity and tone impairment, which would affect the participants’ movements during the experiment.

Fugyl-Meyer Assessment

One of the most widely used quantitative measures of motor impairment (Gladstone et al., 2002). The Fugl-Meyer Assessment (FMA) is a stroke-specific, performance-based impairment index with a total of 5 domains. It is designed to assess motor functioning, balance, sensation and joint functioning in patients with post-stroke hemiplegia. FMA’s applications in research include quantifying severity of effect of stroke and resultant limb movement deficits.

Ethical statement

The project was reviewed and approved by the University of Birmingham's Science, Technology, Engineering and Mathematics Ethical Review Committee. Participants provided written informed consent prior to taking part.

Participant characteristics

Participant code	Handedness	Age	Hemiparetic side	Fugl-Meyer Assessment			Modified Ashworth				Barthel index – 20	Star cancellation - 53
				Motor	Sensation	MMSE	Elbow flexors – 1	Elbow entensors – 0	Wrist flexors – 1	Wrist extensors – 0		
0001AC	Right	51	Left	51	8	30	0	1	1	0	20	38
0002PB	Right	72	Left	58	12	29	1	0	1	0	20	51
0003GJ	Right	55	Left	61	12	28	1	0	1	0	20	54
0004TK	Right	48	Left	53	12	29	0	0	1	0	20	54
0005JNB	Right	68	Left	54	11	30	1	0	1	1	17	54
0006RU	Right	78	Left	53	6	29	1	0	1	0	20	50
0007PF	Right	71	Left	58	12	28	0	0	0	0	20	52
0008GF	Right	80	Right	45	12	25	1	0	1	0	19	54
0009SB	Right	68	Right	64	12	23	0	0	0	0	19	54
0010JB	Right	55	Right	66	12	29	1	0	1	0	20	53
0011MC	Right	78	Right	44	12	21	1	0	1	0	19	54

Table 5.1 Summary of stroke survivor participants characteristics

Data analysis

The data was coded according to hand dominance, tabulated in table 5.2:

Code	Non-dominant	Dominant
Control group	Left hand	Right limb
Stroke survivor	Hemiparetic limb	Non-paretic limb

Table 5.2 Organisation of coding for data analysis

Dependant variables

Limb movement measures

Reaction time (RT): time (ms) from target onset (touchscreen) movement onset (first frame when the speed exceeds 50mm/s).

Movement time (MT): time (ms) from movement onset to movement end (touchscreen).

Response time (ResT): time (ms) from target onset to movement end i.e. (i) + (ii).

Acceleration time (AT): time (ms) from movement onset to time that peak speed (see below) is reached.

Peak speed (PS): the highest speed (mm/s) reached during the limb's movement towards the target.

Deceleration time (DT): time (ms) from the frame peak speed reached to movement end.

Target acquisition error (TE): the distance (mm) from centre of target circle to the touch point.

Coupling relations between the limbs

Absolute and relative inter-limb synchrony was measured at Movement onset; Time of peak speed; Movement end in milliseconds (ms).

Direction of gaze

This was calculated s a proportion of total response time for unimanual conditions and bimanual conditions in the control group and patient group.

Results

Limb movements

Statistical analyses of kinematic data for each of the related dependent variable are presented below. In addition, to assist the reader with these data, figures presenting mean values (and standard error) for each dependent variable are presented as a function of *Condition* (unimanual vs. bimanual congruent vs. bimanual incongruent) and *Side* (non-dominant/impaired vs. dominant/unimpaired) for older adults control participants and stroke survivors (side by side).

Reaction time (RT)

The ANOVA revealed a significant main effect of *Group*, F(1,19)= 6.705, p= .018; RTs were faster for the control group (mean = 529 ms) compared to the stroke group (mean = 801 ms). However, *Group* did not interact with any of the within-subject factors for reaction time (See Fig 5.1).

Acceleration (AT)

The ANOVA revealed a significant main effects for Group F(1, 19) = 16.354, p = .001; stroke survivors had longer ATs (mean = 259ms) than control participants (mean = 147ms). In addition, there were multiple interactions, with most of this involving Group. The AT data are best explained by considering the patterns of data for each group separately (See Fig 5.1). For control participants, there was a significant main effect of *Condition*, F(2,18) = 6.212, p = .009; unimanual ATs were shorter (mean = 138 ms) than both bimanual conditions (congruent, mean = 151 ms; incongruent, mean = 152 ms), though only the latter difference survived Bonferroni correction, p = .036. For stroke survivors, there were significant main effects of *Condition*, F(2,20) = 7.051, p = .005 and *Side*, F(1,10) = 11. 386, p = .007. Unimanual ATs (mean = 212 ms) were shorter than ATs for both bimanual condition (congruent, mean = 268 ms, incongruent, mean = 298 ms). The impaired side (mean = 290 ms) had longer ATs than the unimpaired side (mean = 228 ms).

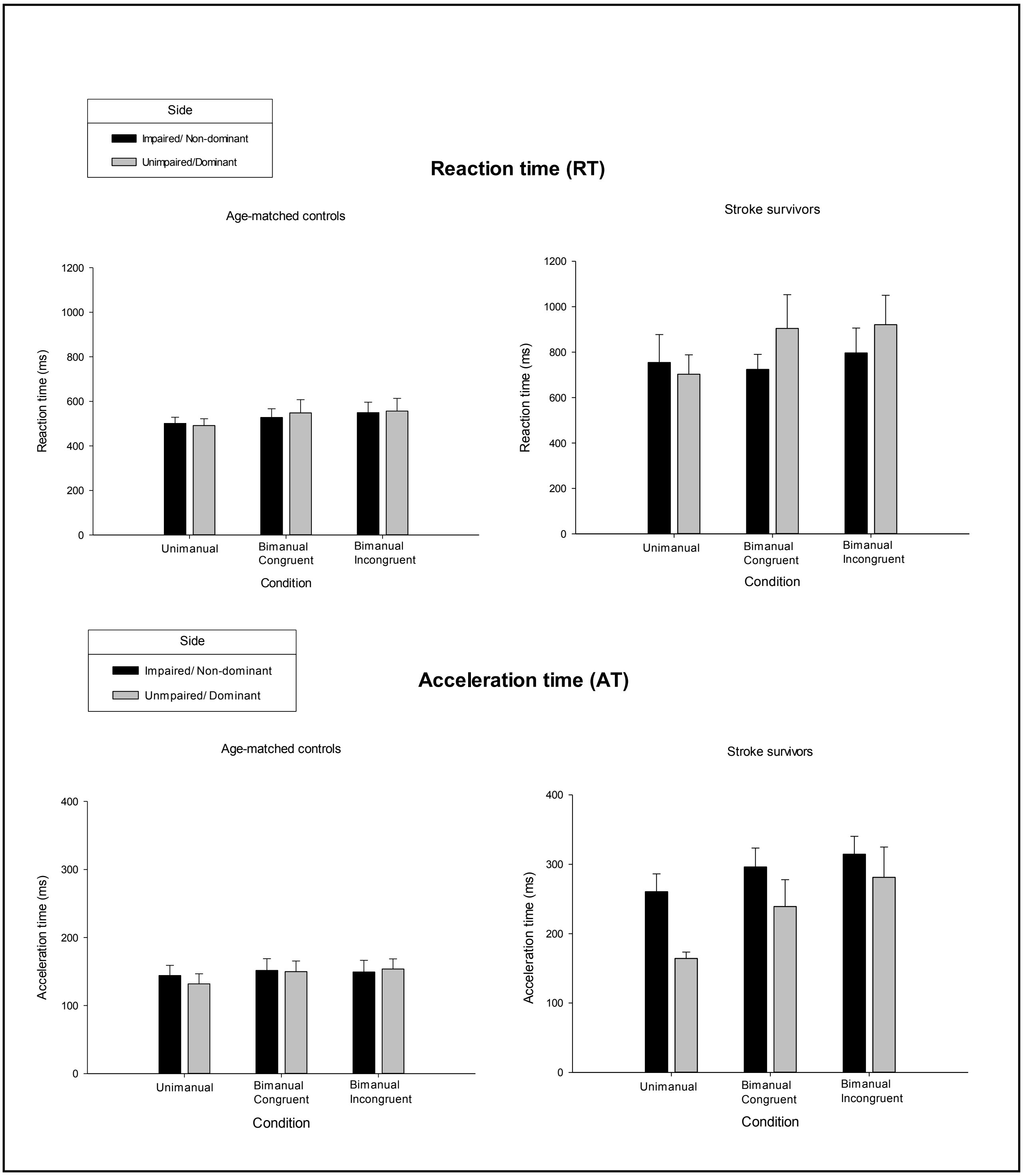


Figure 5.1 Mean Reaction time (RT) and Acceleration time (AT) data as a function of target size for each of the three conditions for Stroke survivor and control group. Error bars denote the standard error of the mean. Asterisks denote statistical significance.

Peak Speed (PS)

Mean PSs for control participants and stroke survivors were 1092 mm/s and 895 mm/s respectively but there was no significant main effect of *Group*, F(1,19) = 3.67, p = .071. However, *Group* interacted with other factors and data were therefore analysed for each group separately. For control participants, the ANOVA revealed significant main effects of Condition F(2, 18) = 20.64, p < .001 and Size F(1, 9) = 16.106, p = .003. Accordingly, PSs for the unimanual condition (mean = 1177 mm/s) were faster than those for bimanual conditions (congruent mean = 1047 mm/s, incongruent mean = 1052 mm/s), p < .01 for both. Additionally, PSs were faster to large (mean = 1109 mm/s) than small targets (mean = 1075 mm/s). Data for stroke survivors showed some similar patterns. Again, there were significant main effects of *Condition*, F(2,20) – 36.13, p < .001 and *Size*, F(1, 10) = 10.28, p = .009; PSs were faster for the unimanual condition (mean = 1015 mm/s) than bimanual conditions (congruent mean = 844 mm/s, incongruent = 824 mm/s), p < .005 for both and were faster to large targets (mean = 911 mm/s) than small targets (mean = 879 mm/s). However, for stroke survivors PSs were faster for the unimpaired limb (mean = 981 mm/s) than the impaired limb (mean = 808 mm/s) leading to a significant main effect of *Side*, F(1, 9) = 10.73, p = .008; see Fig 5.2.

Deceleration (DT)

The ANOVA revealed significant main effects for Group F(1, 19) = 5.730, p = .027, Condition F(2, 18) = 39.232, p < .001, Size F(1, 19) = 44.590 p < .001, and Side F(1, 19) = 14.963, p < .001, as well as Group x Side interaction F(1, 19) = 17.048, p = .002. Patients had longer DTs (mean=1035ms) compared to the control group (mean=738ms). For Condition, DTs were significantly shorter for unimanual movements (mean=712ms) than bimanual congruent (mean = 937ms) and incongruent conditions (mean = 975ms, F(2, 18) = 26.752, p < .001), while the two bimanual conditions' DTs were comparable (p = 1.0); see Fig 5.2. For target Size effect, DTs were faster to large targets (mean= 836ms) compared to small targets (mean= 937ms), F(1, 19) = 44.590, p < .001. Simple effects of the Group x Side interaction revealed DTs for the stroke survivors group were slower for the impaired side (mean = 1250 ms) than the unimpaired side (unimpaired mean = 820ms), F(1, 10) = 18.150, p = .002), while DTs in the control group were comparable for the dominant and non-dominant limbs; see Fig 5.2.

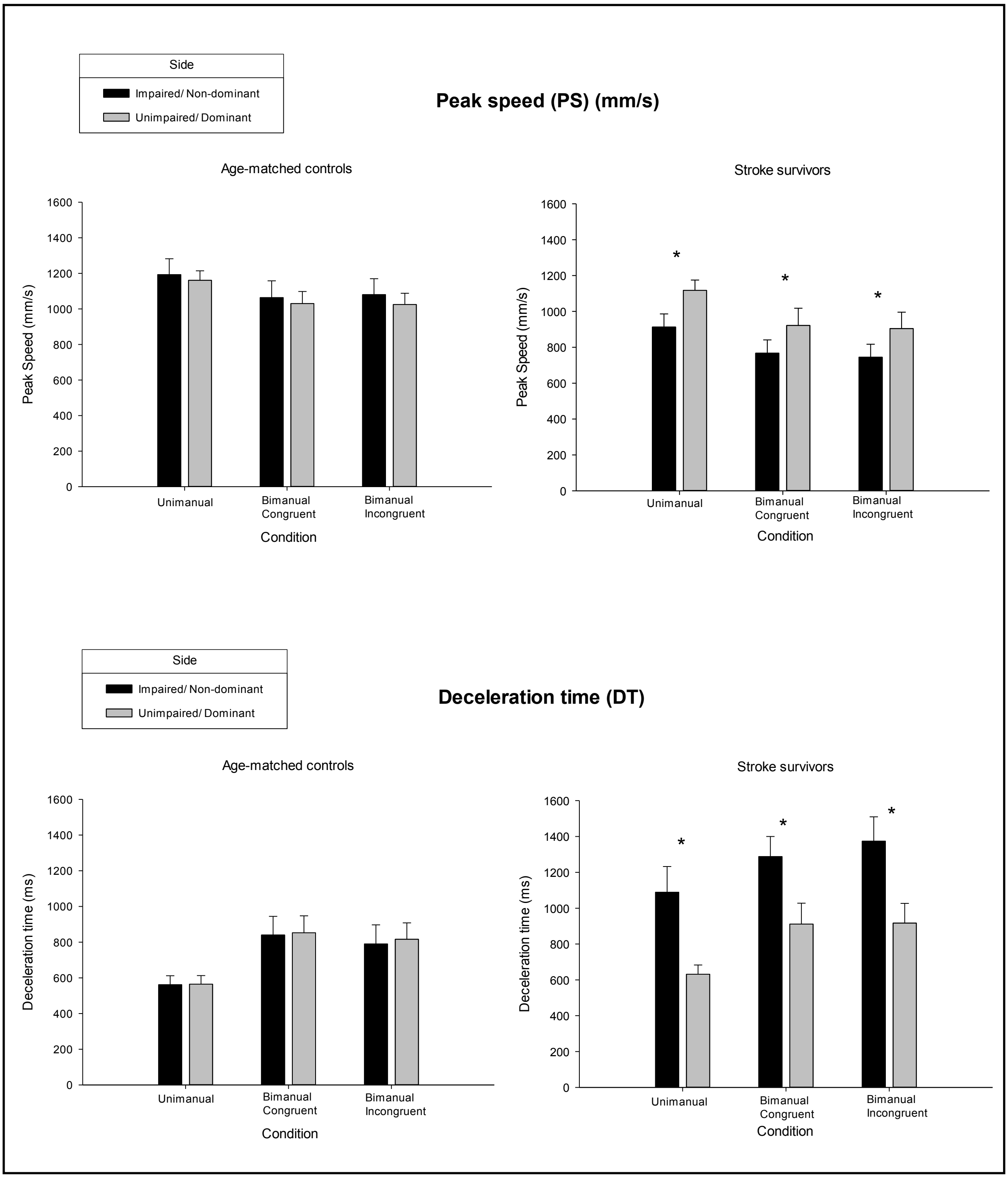


Figure 5.2 Mean Peak Speed (PS) and Deceleration time (DT) data as a function of target size for each of the three conditions for Stroke survivor and control group. Error bars denote the standard error of the mean. Asterisks denote statistical significance.

Movement time (MT)

Across both groups, there was a significant main effect of *Condition*, F(2,38) = 45.49, p < 0.001; unimanual MTs (mean = 883 ms) were shorter than bimanual MTs (congruent, mean = 1177 ms; incongruent, mean = 1195 ms), p < .001 for both. Bimanual congruent and incongruent MTs were comparable (p = 1). Movement times were also scaled for *Target Size* with shorter movements for large targets (mean = 1031 ms) than small targets (mean = 1139 ms) leading to significant main effect of *Target Size*, F(1, 19) = 46.153, p < .001. However, MT analysis was dominated by a significant main effect of *Group*, F(1,19) = 7.94, p = .013, *Side*, F(1,19) = 17.94, p < .001 and a *Group* x *Side* interaction, F(1,19) = 19.44, p < .001. Exploring the simple effects of this interaction reveals two important findings (see Fig. 5.3). Firstly, MTs were significantly longer across all conditions for the impaired limb (mean = 1526 ms) than the unimpaired limb (mean = 1046 ms) in the stroke group, F(1,10) = 21.24, p < .001. In contrast, MTs for the dominant limb (mean = 889 ms) and non-dominant limb (mean = 879 ms) in the control group were comparable, F(1, 9) = .25, p = .631. Secondly, the interaction highlights how MT differences for the stroke group are confined to the impaired limb. Accordingly, while MTs were significantly longer for the impaired limb (stroke survivors) than the non-dominant limb (controls), F(1, 19) = 14.03, p = .001, MTs for the unimpaired limb (stroke survivors) and the dominant limb (controls) were comparable, F(1, 19) = 1.28, p = .27).

Response time (ResT)

Across both groups, there was a significant main effect of *Condition*, F(2, 38) = 49.03, p < .001; unimanual ResTs (mean = 1481 ms) were shorter than bimanual ResTs; p < .001 for both. Paired comparisons also highlighted that bimanual congruent ResTs (mean = 1801 ms) were shorter than bimanual incongruent ResTs (mean = 1879 ms), p = .042. Response times were also scaled for *Target Size*, F(1, 19) = 9.79, p = .006; ResTs for small targets (mean = 1810 ms) were longer than those for large targets (mean = 1630 ms). Again, there was a significant effect of *Group*, F(1, 19) = 12.25, p = .002, *Side*, F(1,19) = 9.79, p = .006 and a *Group* x *Side* interaction, F(1 19) = 11.86, p = .003. The interaction is best explained with reference to Fig. 5.3. For the stroke group, ResTs for the impaired limb (mean = 2284 ms) were significantly longer than ResTs for the unimpaired limb (mean = 1905 ms), F(1,10) = 14.33, p = .004. However, ResTs for the limbs in the control group (non-dominant, mean = 1337 ms; dominant, mean = 1356 ms) were comparable, F(1, 9) = .14, p = .72.

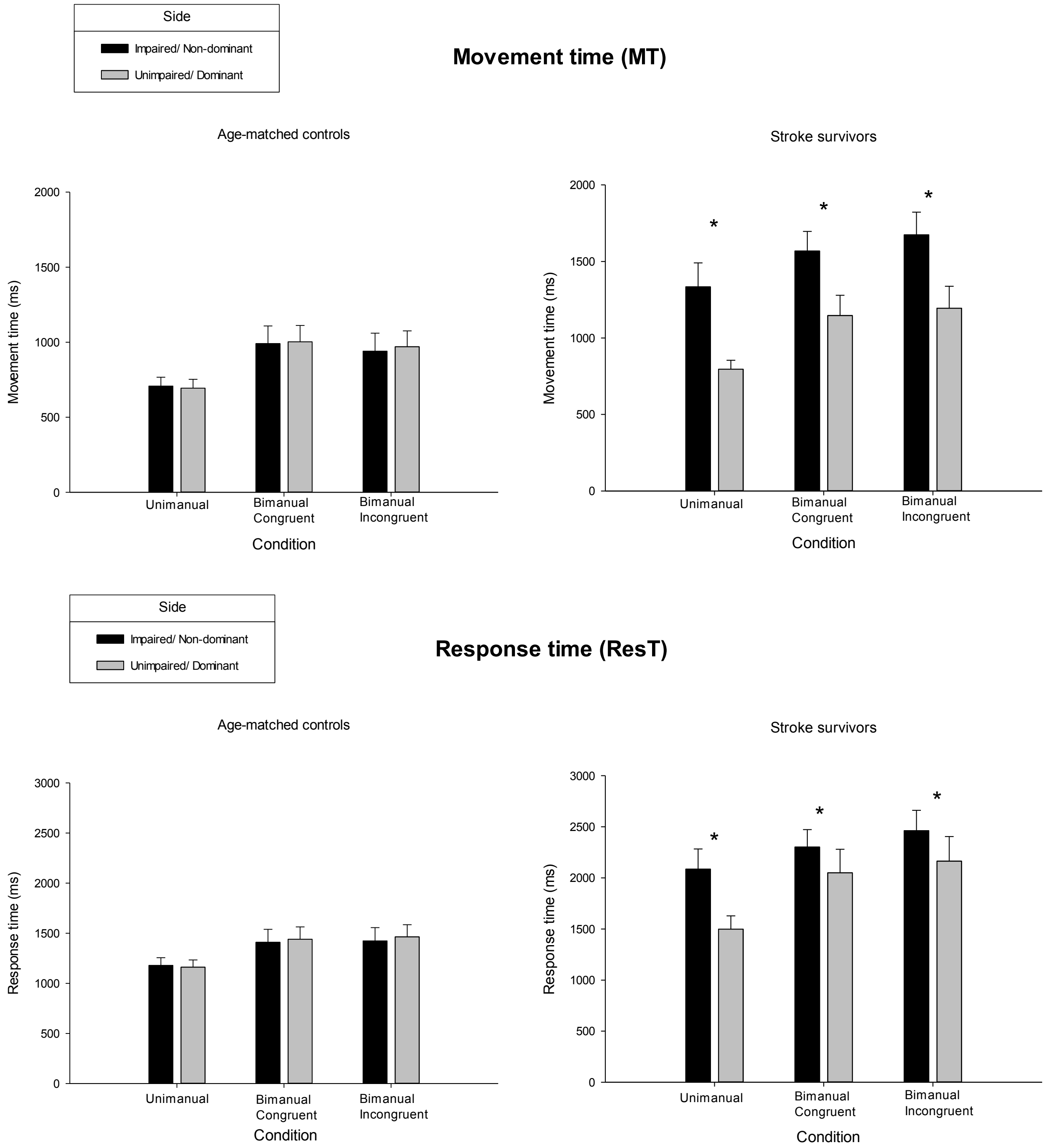


Figure 5.3 Mean Movement Time (MT) and Response time (ResT) data as a function of target size for each of the three conditions for Stroke survivor and control groups. Error bars denote the standard error of the mean. Asterisks denote statistical significance.

Target Error

The ANOVA revealed significant main effects of Group F(1, 19) = 5.142 p = .035, Condition F(2, 38) = 13.42 p < .001, Size F(1, 19) = 5.904 p = .025, and Side F(1, 19) = 5.347, p = .032 and a three-way interaction between Group x Side x Condition F(2, 38) = 4.697, p = .015. These effects are best explained by examining each group separately (see Fig. 5.4). For the control group, accuracy for the dominant (mean = .51 cm) and non-dominant (mean = .55 cm) limbs was comparable, F(1, 9) – 1.02, p = .34. A main effect of *Condition* resulted, F(2, 18) = 12.87, p < .001 as accuracy was poorer for bimanual movements (congruent, mean = .54 cm; incongruent, mean = .64 cm) than unimanual movements (mean = .41 cm), p < .01 for both. Accuracy for the two bimanual condition was comparable, p = .31. Additionally, a significant main effect of *Size* resulted, F(1, 9) = 23.08, p = .001 with superior accuracy shown for movements to the small target (mean = .44 cm) than the large target (mean = .62 cm). There were no interactions.

The picture was quite different for the stroke group. Here, while there was a significant main effect of *Condition*, F(2,20) = 8.52, p = .002, there was also a *Condition* x *Side* interaction, F(2, 20) = 4.58, p = .023. As can be seen in Fig. 5.4, the poorer accuracy for the impaired limb was more pronounced in the bimanual conditions, (congruent, p = .03, incongruent p = .05) than the unimanual condition, p = .12. If one compares across groups, accuracy of the impaired limb in the stroke group (mean = 1.29 cm) was far poorer than the non-dominant limb in the control group (mean = .55 cm), F(1,19) = 4.81, p = .04. However, accuracy for the unimpaired limb in the stroke group (mean = .64) and the dominant limb in the control group (mean = .50) were comparable, F(1, 19) = 2.36, p = .14.

Finally, unlike the control group, accuracy for the stroke group was not significantly scaled for *Size*, F(1, 10) = 2.33, p = .16.

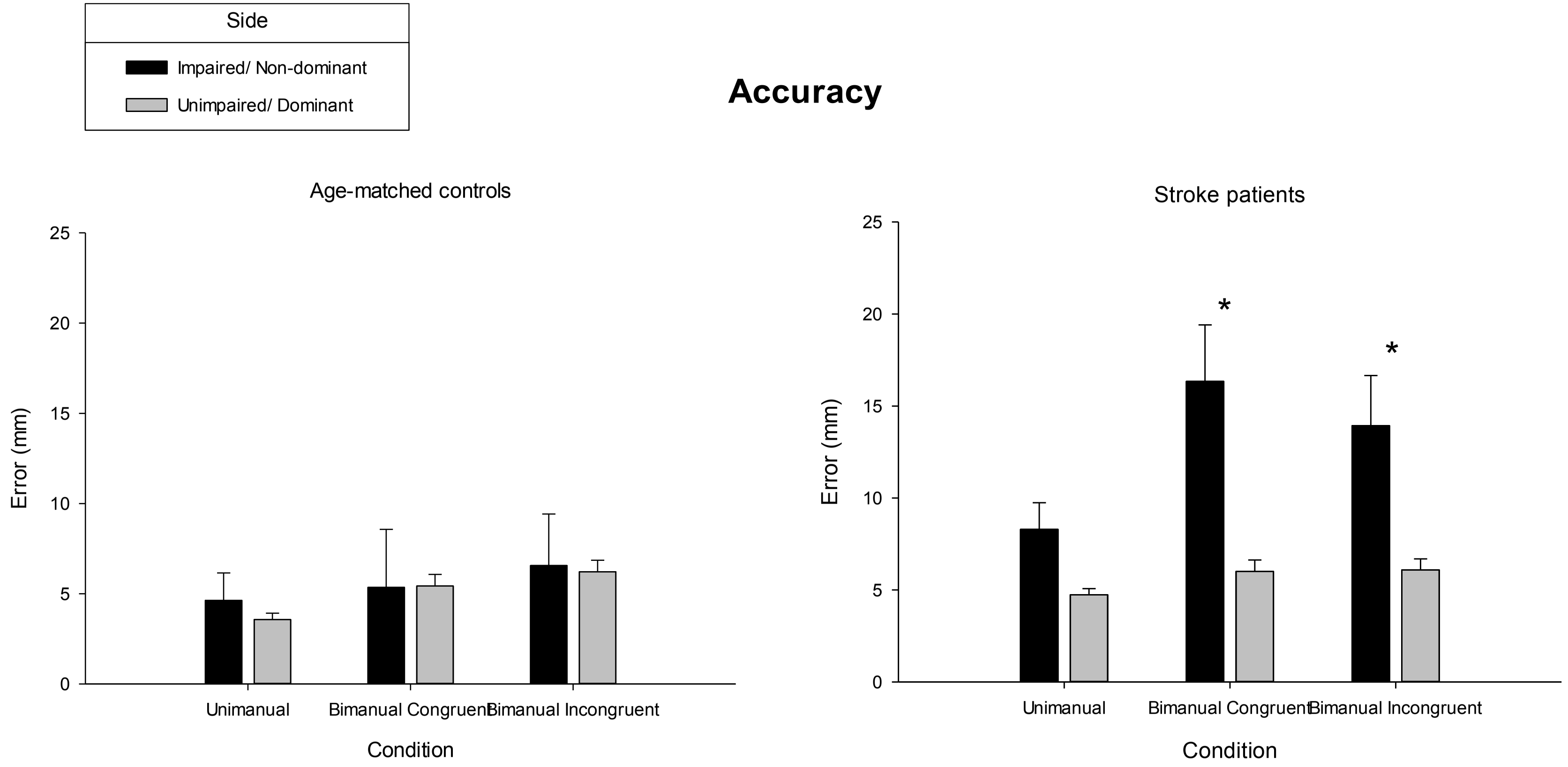


Figure 5.4 Mean Target Error as a function of condition for each of the target sizes. Error bars denote the standard error of the mean. Asterisks denote statistical significance

Limb synchrony

Movement onset synchrony

At movement onset, absolute lag data revealed a significant main effect of *Group*, F(1, 19) = 7.089, p=.015; the control group coupled movements more tightly at movement onset (mean=33ms) compared to the patient group (mean = 379ms). There were no other significant main effects or interactions.

Mean relative lag for the control group was -12ms and was -167ms for the stroke group (see Fig. 5.5); however, there was no significant main effect of *Group*, F(1,19) = 1.94, p= .179 . There were no other significant main effects or interactions.

Time to Peak Speed (TTPS) synchrony

Absolute lag data revealed a significant main effect of *Group*, F(1, 19) = 5.99, p=.024; the control group coupled movements more tightly at TTPS (mean=52ms) compared to the patient group (mean = 392ms). There were no other significant main effects or interactions.

Mean relative lags were -14ms and -126ms (see Fig. 5.5) for the control group and stroke group respectively; however, there was no significant main effect of *Group*,. There were no other significant main effects or interactions.

Movement end synchrony

Absolute lag data revealed a significant main effect of *Group*, F(1, 19) = 21.87, p < .001; the asynchrony between the limbs was far greater in the stroke group (mean = 720ms) than the control group (mean = 129 ms). (F(1, 19) = 21.87, p < .0001). There was also a significant

Congruence x *Non-dominant/impaired Target Size* interaction, F(1, 19) = 5.49, p = .03; with the stroke survivor group showing a greater lead towards the unimpaired hand side; see Fig. 5.5. While size had no effect on asynchrony for the incongruent trials (non-dominant/impaired small, mean = 459 ms; non-dominant/impaired small large, mean = 457 ms), F(1, 19) = .002, p = .96, for congruent trials, movements to small targets (mean = 459 ms) showed greater asynchrony than movements to large targets (mean = 323 ms), F(1, 19) = 13.22, p = .002.

Relative lag data also showed a marked difference between groups, F(1, 19) = 4.857, p=.040; mean lags were -34ms and 292ms for the control group and stroke group respectively (see Fig 5.5). There were no other main effects or interactions.

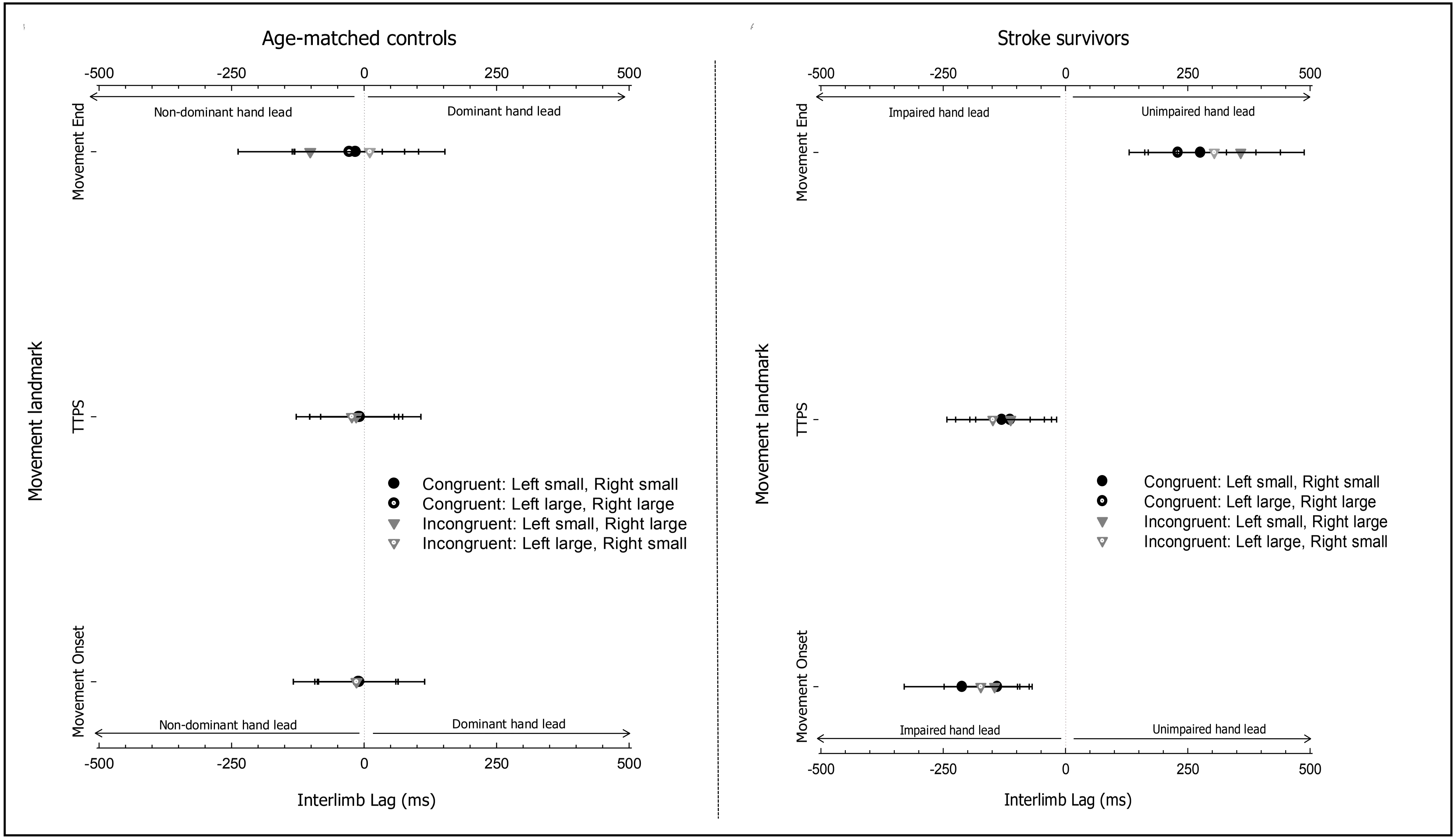


Figure 5.5 Inter-limb asynchrony (relative lead/lag) shown as a function of congruence and phase of movement landmark. Error bars denote the standard error of the mean. Negative values indicate a non-dominant hand lead; positive value indicates a dominant hand lead.

Eye movements

As in Chapter 3, the primary interest here was in whether there was a bias towards one side or the other across response time. Values of -1 and 1 indicated gaze being directed to the non-dominant/impaired or dominant/unimpaired side respectively for the entire response time. However, as visual fixation was always directed centrally at the beginning of each trial, such values were not possible. Before reporting gaze behaviour for bimanual movements, gaze behaviour for unimanual movements was considered. Data were analysed via a 2 x 2 x 2 (Group x Side x Size) ANOVA with repeated measures for the latter two factors. As expected, unimanual movements with the dominant/unimpaired side elicited a marked gaze bias to the same side (mean = .603). Similarly, unimanual movements with the non-dominant/impaired side were associated with a marked gaze bias to that side (mean = -.565). This resulted in a significant main effect of *Side*, F(1,19) = 289.08, p < .001. Data were comparable for both groups, F(1,19) - .83, p = .38 (see Fig. 5.6) and *Size* had no effect, F(1,19) = .19, p = .672; see Fig. 5.6.

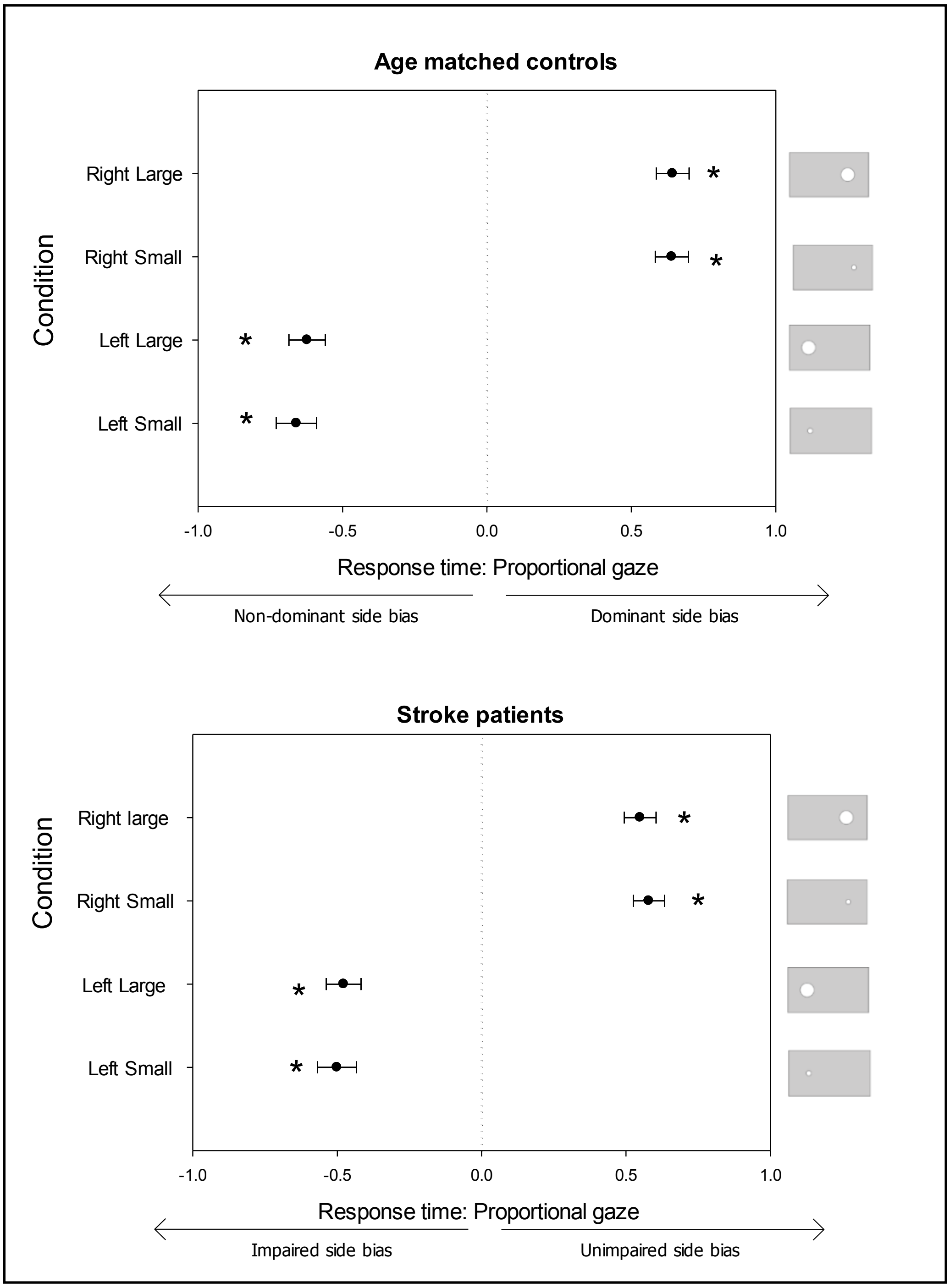


Figure 5.6 Direction of gaze as a proportion of total response time for unimanual conditions in control group and patient group. Error bars denote the standard error of the mean. Negative values indicate gaze bias to the left side; positive values indicate a gaze bias to the right side.

For bimanual movements, the data were analysed via a 2 x 2 x 2 ANOVA where *Group* (control vs. stroke), *Congruence* (congruent vs incongruent) and Size of dominant/unimpaired target (small vs large) were the factors; repeated measures for the latter two factors. Data revealed a significant main effect of *Size* (F(1, 19) = 10.949, p=.004) and a *Congruence* x *Size* interaction, F(1, 19) = 24.56, p < .001). The interaction was best explained by referring to Fig 5.7. As can be seen, there appeared to be little bias to one side or another for congruent movements and no effect of *Size*, F(1,19) = 2.71, p = .116. However, for incongruent movements, gaze was biased to the side where the small target was presented, F(1,19) = 26.07, p < .001. Importantly, there was no effect of *Group*, F(1, 19) = .09, p = .767 and *Group* was not involved in any interactions; the pattern of data for stroke survivors was consistent with the control group.

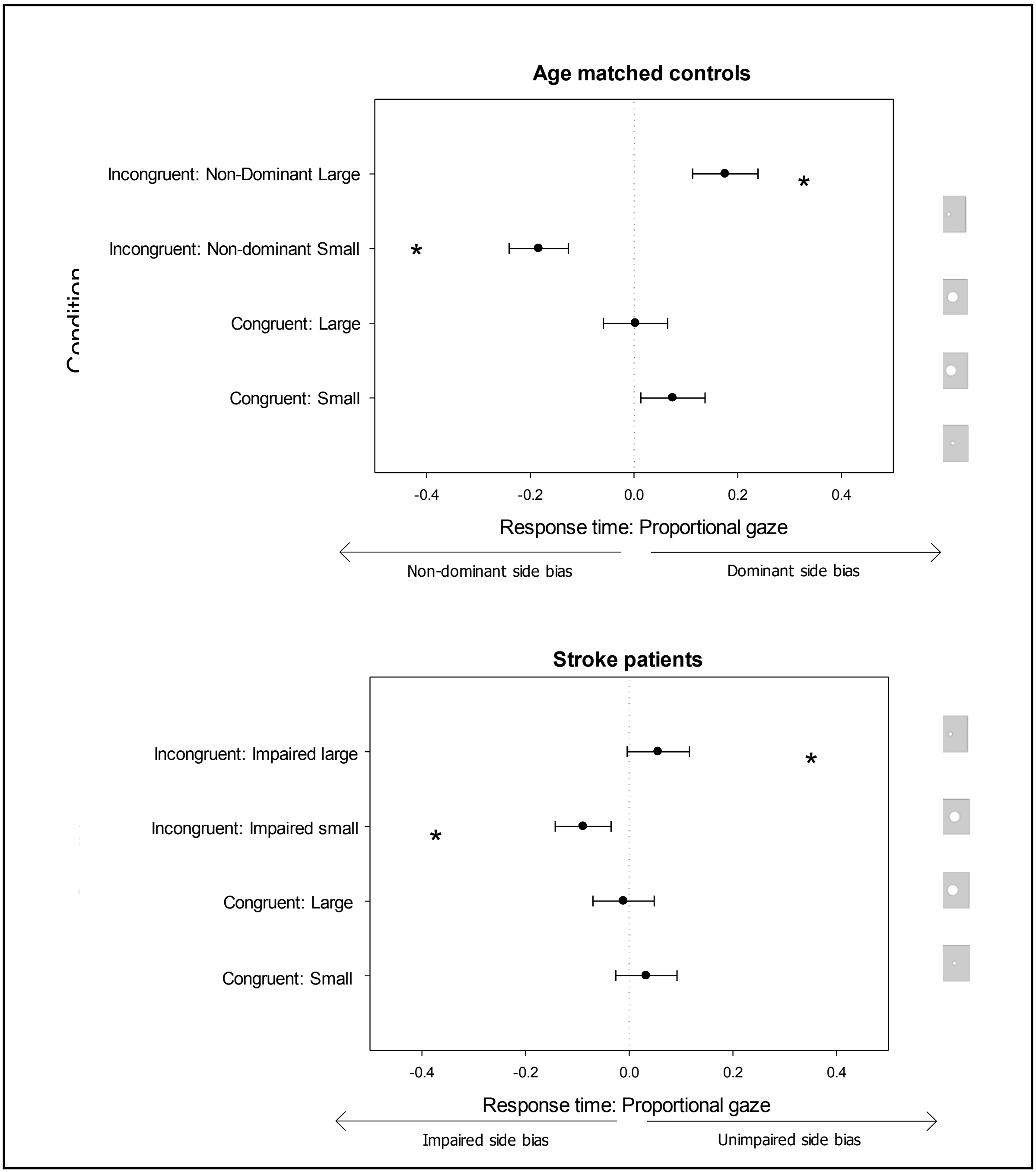


Figure 5.7 Direction of gaze as a proportion of total response time for bimanual conditions in control group and patient group. Error bars denote the standard error of the mean. Negative values indicate gaze bias to the left side; positive values indicate a gaze bias to the right side.

Discussion

To date, no other published studies have examined limb and eye movements during bimanual tasks in stroke survivors; this is noteworthy given the importance of visually guided bimanual activities for carrying out daily functional activities, where stroke survivors tend to have difficulties (Wade et al., 1983, Collins et al., 2018, Stewart et al., 2019). Eleven stroke survivors with varying levels of impairment were recruited to participate in the novel task as detailed in chapter 2. We investigated how stroke survivors visually navigated unimanual and bimanual reaching movements given the impairment of a hemiparetic limb. Stroke survivors were all able to perform reaching movements using their hemiparetic limb when moving unimanually; of particular interest was the interaction between the inter-limb competition for visual resources and interaction between the hemiparetic limb and unaffected limb in planning and execution of bimanual movements. One would predict that hemiparesis in stroke survivors would manifest itself in poorer task performance (i.e. slower and less accurate) for unimanual movements, resulting in slower and less accurate limb movements compared to the unaffected limb. For bimanual movements, despite the relatively mild impairment in one limb, it was postulated that that stroke survivors would retain the drive to synchronise limbs and adapt movement strategy be able to perform coordinated bimanual movements in the following manner. Firstly, the movement would be modified to optimise coupling, in that the unaffected limb would be slowed down to be temporally synchronised with the hemiparetic limb. Secondly, albeit mild, the hemiparesis renders the required movement comparatively more challenging for the affected limb. As gaze distribution throughout movement is modulated by task difficulty (chapter 3), one would expect that stroke survivors compensate for the deficit by directing a greater proportion of gaze during bimanual movement towards the hemiparetic side (compared to the unimpaired side), which has a higher index of difficulty, to optimise task performance.

As hypothesised, results showed slower and less accurate unimanual movements for stroke survivors overall were driven wholly by the slower and less accurate hemiparetic limb. However, unanticipated yet noteworthy findings emerged for gaze behaviour and temporal coupling between the limbs for bimanual movements; stroke survivors appeared to execute movements in a manner that did not account for their motor deficit. Contrary to our predictions, eye movements were not biased towards the hemiparetic limb, and although temporally coupled at movement onset, limbs became temporally uncoupled as movement unfolded whereby the hemiparetic limb lagged significantly behind the unaffected limb at movement end. We postulate that an implicit lack of full awareness for hemiparesis (anosognosia) may be a possible explanation for the observed behaviour of stroke survivors. Below, results are discussed in terms of kinematics and accuracy findings which were as hypothesized, followed by unexpected findings on visual gaze behaviour and bimanual coordination as observed by inter-limb lag during bimanual movements.

Hemiparesis and the cost of bimanual movements

Overall, as per hypothesis, kinematic measures showed slower and less accurate unimanual movements for the hemiparetic limb in stroke survivors compared to the unaffected limb, this is consistent with previous studies in the field (Wu et al., 2000, Alt Murphy et al., 2011, DeJong and Lang, 2012, Stewart et al., 2019) with the meta-analysis by Collins et al. (2018) concluding that stroke survivors were slower and less accurate in reach to target movements. Similarly, results of this study showed that in unimanual conditions, despite no stringent time constraints on movement and the availability of visual resources to guide the limbs to their respective targets, the hemiparetic limb in stroke survivors performed more poorly than the non-dominant limb in the control group. In contrast, accuracy for the unimpaired limb in the stroke group and the dominant limb in the control group were comparable, highlighting the selective deficit of the hemiparetic limb. The poorer accuracy for the hemiparetic limb has been attributed to several factors which affect the visuomotor systems ability to use sensory-motor feedback and impair the fine motor control of the limb; these include neuromotor noise from the hemiparetic arm movements (McCrea and Eng, 2005), deficits in somato-sensation (Carey and Matyas, 2011) and proprioception (Semrau et al., 2013). In this study, although the hemiparetic limb impairment was relatively mild and participants could complete reaching movements whilst visually guiding the limbs to the targets without time constraints, stroke survivors still showed significantly poorer accuracy for the impaired limb.

For bimanual movements, as also observed in chapter 3 and chapter 4, participants were less accurate in comparison to unimanual movements, with results showing the typical cost as task demands increased; this can be attributed to the competition for visual resources that arises when the motor system has to attend to two separate targets during bimanual movements (Jackson et al., 1999, Riek et al., 2003, Srinivasan and Martin, 2010). For stroke survivors, findings suggest that the accuracy cost of bimanual movements is carried by the impaired limb (almost) entirely, as the impaired limb is less accurate than the unaffected limb, and the unimpaired limb is comparable in error to the non-dominant limb in the control group.

In addition to the lower accuracy for bimanual movements compared to unimanual movements, findings also revealed a temporal cost to performing bimanual movements. For stroke survivors, although movement parameters for both the hemiparetic and unaffected limb are comparable at movement onset, as the limb movement progressed following the reaction time phase, measures of acceleration, deceleration, movement time, response time and peak speed exhibited longer times and slower speed compared to unimanual conditions. Particularly in stroke survivors, inter-limb relations showed poorer performance for the hemiparetic limb compared to the unaffected limb. Interestingly, the unimpaired limbs kinematics appears to show comparable movement time to the control group during unimanual movements. For bimanual movements, the impaired limb appears to be much slower in comparison to the unaffected limb; suggesting that within the slower movement parameters observed in stroke survivors, the temporal cost of bimanual movements is modulated largely by the hemiparetic limb. In comparison to findings from previous studies and chapter 3, in unimpaired individuals, this cost is typically shared across both limbs with a reduction in accuracy and longer movement times. However, results from this chapter show the cost of bimanual movement, driven by the visual requirement of two separate targets, is borne entirely by the hemiparetic limb; comparable with the control group’s dominant limb, the unimpaired limb in stroke survivors is seemingly unaffected in movement execution during bimanual movement whilst the hemiparetic limb bears the significant temporal cost of movement.

The observed cost of bimanual movements is reported by Jackson et al. (1999), findings in earlier Chapters 3 and 4, and a study with stroke survivors (Rose and Winstein, 2005), with the limbs temporal synchrony at movement end. However, the key difference in findings in this study is the asynchrony between the limbs at movement end. A similar study by Rose and Winstein (2005) showed temporal coupling between the limbs, however, in the current study stroke survivors appeared to show a lack of awareness of deficit which may have resulted in a movement strategy that did not accommodate the hemiparetic limbs weakness and thus execute temporally uncoupled movements. The task differences between Rose and Winstein (2005) and the current study may explain the markedly different findings in temporal synchrony between the limbs at movement end. For instance, Rose and Winstein (2005) used a single, centrally located reaching target which used IR switches as a measure of fixed accuracy. As the target switches were in either on or off positions, reaching onto the targets may not require saccades or changes in eye position. Furthermore, the central location of the target also dictates that, even in bimanual conditions, changes in eye position may not be required to reach movements towards the target whereas the current study protocol required significant contribution of vision in reach movements to separate targets. The bimanual cost and asynchrony between limbs is discussed below in relation to the visual control of bimanual movements.

Breakdown in bimanual coordination: weighting of motor and visual resources

In an individual with hemiparesis, in addition to the cost of bimanual movement associated with the planning and execution of movements, the visuomotor system has to balance the 'drive to synchronise' both limbs during bimanual movements although each limb has markedly different movement capabilities. Based on findings of previous studies (Rice and Newell, 2004, Rose and Winstein, 2005, Messier et al., 2006), and given the relatively mild hemiparesis of stroke survivors, it was hypothesised that the unimpaired limb in the stroke survivors group would accommodate its movements to match the temporal constraints brought about by the hemiparetic limb. However, results showed that although the limbs were in temporal synchrony at movement onset, as the movement unfolded the limbs became more asynchronous.

A possible explanation for this could be inattention to the impaired limb during bimanual movements may be related to learned non-use (Taub et al., 2006). The hemiparesis caused by stroke was chronic in nature for all participants in the current study; therefore, the prioritising of the unimpaired limb may be a learnt behaviour. Studied by Taub et al. (2006), the learned non-use theory postulates that although the hemiparetic limb may be capable of completing a range of movement, however, an individual compensates by using their unaffected limb more over time, thereby learning to not use their hemiparetic limb. In the current study, participants were able to complete unimanual movements using the impaired limb, however when faced with a bimanual task, the unaffected limb was prioritised. In terms of movement planning, the synchronous reaction time for the two limbs suggests a motor plan that intended to temporally couple the limbs; however, this motor plan is not executed after movement onset. Absolute temporal asynchrony between the limbs increased as the movement progressed, and the direction of this asynchrony showed the unaffected limb leading at TTPV with an even greater lead at movement end. As the motor planning or intention phase appears to be intact, the breakdown in coupling may be explained by a deficit of awareness of hemiparesis. Hirsch et al (in press) advocate for inclusion of bimanual movements as a diagnostic tool for learned-non-use observation in stroke survivors, which have also been advocated in recent years to examine motor awareness issues (Garbarini et al., 2013).

In addition to stroke survivors not compensating for their motor deficit by slowing their unimpaired limb to allow coupling, eye movement data showed that vision was also not biased towards the affected side to enhance task performance as had been predicted. In line with findings from Chapter 3, visual resources are modulated by the difficulty of the experiment condition and vision is biased towards the smaller (more difficult) target on either side in incongruent conditions. As the reduced motor capability of the hemiparetic limb renders the index of difficulty higher in comparison to the unaffected limb, it was predicted that the hemiparetic limb would be the modulating factor for vision rather than the targets' index of difficulty. Contrary to the experiment's prediction, it was found that stroke survivors' eye movements were entirely consistent with those seen in the unimpaired control group and with related data presented in Chap 3; stroke survivors distributed equal visual share to both the unimpaired and hemiparetic limb. Moreover, similar to younger unimpaired population as reported in Chapter 3, stroke survivors reliably directed gaze towards the small sized target during incongruent bimanual conditions, showing that vision is modulated by index of difficult in incongruent conditions and not by the very limited capability of the impaired limb. Meadmore et al. (2018b) found that during unimanual reaching movements in hemiparetic stroke, the impaired limb movements were less likely to be completed compared to the unimpaired limb movements. Furthermore, an increase in eye movements to the impaired limb was also observed, suggesting that the hemiparetic limb requires a greater share of visual guidance in reaching movements compared to the unimpaired limb. In this chapters study, there appeared to be no change in the allocation of visual resources for stroke survivors above and beyond what was seen in unimpaired individuals as a result of the different indices of difficulty driven by the size of the targets, findings which appears unintuitive given the obvious movement deficit for the hemiparetic limb.

The temporal coupling observed at movement onset suggests intention to temporally couple the limbs whilst visually guiding onto their respective targets, which appears to not account for the severity of deficit in the impaired limb. A possible explanation for findings reported may be explained by anosognosia, an impairment in deficit awareness. Garbarini et al. (2012a) describes anosognosia as a clinical condition in which movement awareness appears to be altered, whereby the patient is unaware of the deficit or the extent of deficit of their impaired limb. Studies report clinical incidence of anosognosia for hemiparesis ranging from 33% (Bisiach and Geminiani, 1991) to 58% (Cutting, 1978) in stroke survivors, with typical behaviour showing lack of awareness of the extent of movement deficit of the impaired limb. For this study, stroke survivors were not clinically diagnosed with anosognosia as during the screening there was no suggestion that participants had related problems, furthermore, a majority of research on anosognosia has been undertaken on stroke survivors with hemiplegia or severe hemiparesis whereas the participants in this study showed mild hemiparesis. A perception and action study review by Frith et al. (2000; Fig 4), proposes that in stroke survivors with anosognosia, the motor plan for the impaired limb remains intact and that deficit falls within the action part of the movement as opposed to the perception of movement. Empirical evidence comes from Garbarini et al. (2012b), who found that in a bimanual line-circle drawing task, ovalisation effects for the contralateral limb were observed in unimpaired controls and patients with AHP, but not for hemiplegic or patients with motor neglect, suggesting that patients with AHP seemingly retained the ability to generate sufficient motor intentions/plans for the affected limb (although they did not move the hand).

In the current study, in addition to the decoupling of the two limbs during bimanual movements, a lack of awareness of deficit in stroke survivors with mild hemiparesis are also reflected in the eye movement results, which are conducted in a manner that did not appear to account for the greater visual guidance that the hemiparetic limb requires (Meadmore et al., 2018b). Case studies of subjects with sensorimotor deficits appear to suggest similar behaviour that may be attributed to an unawareness of deficit. For instance, Jackson et al. (2000) presents a deafferented patient, who is able to execute unimanual movements using the unimpaired and impaired hand, whereas simultaneous bimanual movements presented a challenge. Movement initiation for the two limbs was coupled, even in conditions where it was not the most efficient motor plan to execute. The behaviour is attributed to weighting of sensimotor cues biased towards visual input rather than proprioceptive input for the impaired limb, which was reduced due to the impairment (hemianesthesia). Similar findings that suggest a lack of awareness of deficit in a stroke survivor with limb impairment comes from Punt et al. (2005a), who found that although a patient with motor neglect was able to complete unimanual movements with relative ease, during bimanual movements attentional bias towards the unimpaired hand was observed in reach to grasp movements. Limb movement behaviour observed in the case studies by Jackson et al. (2000) and Punt et al. (2005a) appear to be disproportionate to the nature of the subjects deficit, and although has been explained by biased competition in the case of patient MM (Punt et al., 2005a) and sensorimotor cues bias in patient DB (Jackson et al., 2000), in conjunction with findings reported in this chapter, the findings can be attributed to a lack of awareness of limb deficit or disability.

Possible limitations and future directions

Although the eleven stroke survivors were screened thoroughly and met the stringent inclusion criteria, with Fugyl-Meyer scores in the range of 46 to 66 that fit into the ‘mild to moderate’ bracket of impairment, we observed some variability in the kinematic measures. Stroke is a heterogeneous disease by nature, with hemiparesis and thus impairment being different in each person, so the variability in behaviour was to be expected. However, the approach may benefit from more stringent or strictly controlled movement inclusion criteria, whereby participants are allocated into further subgroups depending on their limb movement capability as based on their FM score. Such approach would allow for a more focused study of how the extent of movement impairment (based on FM score) impacts naturalistic reaching movements. Moreover, future research may consider individual cases or subgroups for distinct patterns and behaviour. For instance, subgroups which consider the difference in task performance by hemisphere damage may be of interest. As discussed in Chapter 4, both hemispheres contribute to bimanual movement control and coordination; however, contribution of each hemisphere is weighted unequally for motor control and coordination of reaching movements. For instance, the right hemisphere is hypothesized to play a specialized role in endpoint control (Sainburg and Schaefer, 2004) whereas the left hemisphere is implicated in proprioception. In stroke survivors, research (Schaefer et al., 2007, Mani et al., 2013) shows that endpoint error is greater after right brain damage compared to left brain damage. The reach to point task from the current study conducted with such subgroups or individual cases will illuminate the relative weighting of contribution of each hemisphere to coordination and control of bimanual movements.

Another area of possible improvement in the protocol that we identified was our method of measuring eye movements. Within the context of our study, the EOG protocol was adequate for the purposes of our intended outcomes. We were able to measure the bias of visual resources between the two sides during movements precisely, and with high temporal resolution. However, for future directions, a similar set up with higher spatial resolution of visual direction may be illuminating in providing qualitative information on gaze behaviour within each trial. For example, the number of saccades made in total throughout the movement, and relative time spent gazing towards the limb compared to target will offer further insight into visuomotor control of upper limb movements.

Conclusions

This is the first study to examine the visual control of unimanual and bimanual movements in stroke survivors with mild hemiparesis. Stroke survivors were able to complete unimanual movements with their impaired limb, albeit more slowly and less accurately than the unimpaired limb and the control group. For bimanual movements, results revealed the challenges in bimanual coordination for the visuomotor system during reaching movements following stroke; the findings suggest that the cost of bimanual movements is borne almost entirely by the hemiparetic limb in stroke survivors, who unpredictably, did not appear to make compensatory adjustments for their limb impairment; visual attention was not biased towards the hemiparetic limb as expected. A lack of full awareness of their deficit (anosognosia) may explain the breakdown in temporal coupling and the observation of vision not being used to guide the impaired limb to respective targets. The current research findings have implications for rehabilitation as full awareness of deficit is vital for effective upper limb research in stroke survivors.

Chapter 6: General discussion

This thesis aimed to improve our understanding of how the visuomotor system controls and coordinates unimanual and bimanual movements using overt and covert visual attention in young adults. Furthermore, the thesis presented the first study to explore the role of eye movements during bimanual reaching movements in stroke survivors with mild hemiparesis. The rationale was to build on previous research in the field and add to the current knowledge base on factors that underpin control of bimanual movements, which has implications for upper limb rehabilitation following stroke. A novel experiment was developed; which improved on previously published experimental paradigms in the field by addressing the measurement of gaze behaviour during reaching movements. The task allowed exploration of the interaction between gaze behaviour and limb movements as individuals made unimanual and bimanual aiming movements. This chapter summarises findings from the experimental chapters, followed by discussion of topics that arose from these findings. Further to this, theoretical and applied implications of the research are highlighted, followed by suggestions for future research directions.

Summary of experimental chapters

The first experiment (Chapter 3) explored how overt visual attention is used to coordinate unimanual and bimanual movements to targets of different sizes in left and right-handed participants. Resulting data showed that although typical patterns of movement as previously reported were observed, asynchronies that emerged between the two limbs towards the latter part of the bimanual movements were driven largely by visual demands of the smaller target in incongruent conditions. The visuomotor seemingly balances the drive for synchrony between the two limbs with the necessity to visually guide the limbs onto two different locations. Here, there was a tendency for the limb reaching towards the smaller, more difficult target to lead the other limb, and the proportion of gaze during movement was towards the same side.

The second experiment (Chapter 4) explored how covert visual attention is used to coordinate reaching movements in right-handed participants, with participants' vision fixed centrally to control for overt shifts in gaze. Kinematic results showed faster movement parameters in the absence of overt shifts in gaze, when movements are under covert control because of less precise visual guidance, which also resulted in reduced accuracy over all, and greater synchrony between the two limbs than seen in Chapter 3. Of particular interest here was the unexpected findings of superior accuracy for the non-dominant left limb, which was attributed to the left limb being more adept in using proprioceptive feedback and being less reliant on visual guidance that the dominant right limb, which showed a greater proportion of errant saccades in its direction. During bimanual movements, the sensory input was weighted in favour of proprioception, as relative visual input was restricted due to gaze being fixed centrally. This explanation also lends itself to comprehensible speculative explanation for another unanticipated finding of bimanual movements being more accurate than unimanual movements.

The final study, Chapter 5, presented the first study to examine the visual control of unimanual and bimanual movements in stroke survivors with mild hemiparesis. Results showed that stroke survivors were able to complete unimanual movements with their impaired limb, albeit more slowly and less accurately than the unimpaired limb. Interestingly, stroke survivors did not appear to make compensatory adjustments for their limb impairment; as visual attention was not biased towards the hemiparetic limb as the hypothesis had predicted. Anosognosia, a lack of full awareness of deficit, may explain these unexpected findings.

Discussion of key findings

Basic kinematic findings

In line with previous findings in the field (Jackson et al., 1999, Bruyn and Mason, 2009, Miller and Smyth, 2012, Coats and Wann, 2012), unimanual and congruent bimanual limb movements towards small targets with higher index of difficulty were slower comparable movements to larger targets, which had a lower index of difficulty, reflecting Fitts Law (Fitts, 1954). However, Fitts Law was violated when making bimanual movements where the index of difficulty was different for the two limbs; instead, here coupling between the limbs appeared to be prioritised. However, small but reliable asynchronies emerged during the latter stages of bimanual movements and were most pronounced for the incongruent conditions.

Furthermore, findings across experiment were revealing regarding the *cost* of bimanual movements (the finding that bimanual movements are generally slower than comparable unimanual movements (See Table 3.1 and Fig. 5.3) (Jackson et al., 1999, Punt et al., 2005b). This *cost* also extended to movement preparation as revealed by relatively slow reaction times for bimanual movements in comparison to a unimanual movements (Chapter 3 and 5) and consistent with (Blinch et al., 2018); See Table 3.1, and Fig. 5.1). However, by observing data across this thesis, it can be seen that the typical *cost* of bimanual movements appears to be rooted in the visual demands of the task. In Chapter 4, where participants were limited to covert attention, reaction time (see Fig. 4.3) showed no *cost* and the *cost* was greatly reduced for movement time (see Fig. 4.4) While this has previously been shown to be the case (e.g. Miller & Smyth, 2012), data in this thesis provide a compelling demonstration of this and suggest that a continuum exists in relation to asynchrony between movements where there is full vision (asynchrony more pronounced) and where there is no vision (minimal/no asynchrony).

Relations between eye movements and asynchrony

As highlighted in previous studies (Bruyn and Mason, 2009, Miller and Smyth, 2012, Coats and Wann, 2012), although means of asynchrony are useful in making comparison with previous literature, exploring temporal asynchrony on a trial-by-trial basis offers a more meaningful insight into relations between the limbs during bimanual movements. For experiments in the thesis, both signed and absolute measures were explored; with analysis revealing interesting findings.

Results from Chapter 3 (Fig 3.2, pg. 53), Chapter 4 (Fig 4.7, pg. 88), and Chapter 5 (Fig 5.5, pg. 129) show that at bimanual movement onset the limbs began the movement in temporal synchrony as per established literature predictions (Kelso et al., 1979, Swinnen, 2002). However, as the movement progressed, signs of asynchrony between the limbs emerged. Previous studies suggest that asynchrony can be a result of factors such as task demands (Miller and Smyth, 2012, Bruyn and Mason, 2009, Bingham et al., 2008); laterality (Sainburg, 2002, Goble and Brown, 2008a) or impairment (Jackson et al., 2002b, Punt et al., 2005a) can influence the desynchronisation of the limbs.

Under overt (Chapter 3) and covert (Chapter 4) attentional control in unimpaired young individuals, the progressive desynchronisation of the two limbs is modulated by task demands; the requirement for simultaneous visual feedback to two separate targets is the bottleneck which drives the asynchrony between the two limbs. In both cases, the smaller targets for the non-dominant limb modulated attentional demands, which also lead to prioritisation of the limb with the more demanding task leading the movement (Duncan et al., 1997).

Of surprise and interest were unexpected findings observed in the stroke survivor participants (Chapter 5), which showed that movement patterns did not follow the conventional pattern discussed above. For individuals with a mild hemiparesis deficit, although temporally coupled at movement onset and at TTPS, the unimpaired limb tended to lead at movement end. The visuomotor system seemingly *neglected* the slower and weaker hemiparetic limb as movement progressed; this was postulated to result as a consequence of unawareness of deficit (anosognosia), whereby the unimpaired limb leading at movement entirely accounted for the temporal asynchrony at movement end.

Attentional control and relations with accuracy

For unimpaired participants, under overt visual control, gaze distribution was modulated by the task conditions; the limb which was leading towards smaller target in incongruent conditions also had a greater allocation of vision biased towards it throughout the trial, and consequently showed lower error. Interestingly, where participants' vision was fixated centrally, a higher weighting of proprioception in the control of movements appears to have occurred. For stroke survivors, recent research has explored bimanual movements to highlight the problems relating to anosognosia following stroke (Garbarini et al., 2012a, Garbarini and Pia, 2013), and for individuals with mild hemiparesis, it appeared an intuitive finding that the limb with impairment was poorer in accuracy in comparison to the unimpaired limb. However, although no evidence of cognitive problems and certainly no explicit indication of anosognosia for hemiparesis was observed in participants, the relative gaze allocated to each limb during bimanual movements was unanticipated and seemingly unintuitive given the obvious sensorimotor deficit of one limb. One would expect, that the hemiparetic limb to be allocated a greater share of visual resources as it is generally weaker and slower (Krakauer and Carmichael, 2017). With reference to Fig 5.7, the visual demands during task performance were modulated by the smaller target in incongruent conditions for stroke survivors, in similar fashion to unimpaired individuals using overt (Fig 3.3, Chapter 3) and covert (Fig 4.9, Chapter 4) attentional control. Surprisingly, for congruent conditions, where both targets were of equal difficulty, stroke survivors did not allocate any more visual resources to the impaired side (i.e. visual resources were distributed equally to the impaired and unimpaired sides).

For movements under overt control in unimpaired young individuals, the limb which received a greater share of visual guidance in incongruent conditions was more accurate and tended to lead the other limb at movement end too. Similar findings were reported for movements under covert control, where although the non-dominant limb is more accurate overall, the limb targeted towards the smaller target in incongruent conditions is leading towards movement end. For stroke survivors however, there appeared to be a disengagement between the limb impairment and limb behaviour observed. Alongside the impaired limb not being directed a greater share of visual resources; it also appears that the movement pattern observed does not account for the impairment; whereby the unimpaired limb leads at movement end. The findings suggest that neurological impairment can affect the visuomotor systems planning as well as execution of movement.

Theoretical and practical implications

Firstly, the data supports previous theoretical propositions of the cost of movements, and findings suggest that temporal inter-limb asynchrony is being driven by the visual requirements of bimanual movements. Secondly, where overt gaze shifts occur, the index of difficulty in incongruent tasks modulated performance, and a relationship between the limbs' behaviour is observed, whereby the limb that leads movement is also tasked with reaching the target of higher index of difficulty.

For stroke survivors, although the task elicited coupled movements at movement onset, as the movement progressed the limbs became much more desynchronised than was hypothesised. The results, albeit unexpected and surprising, offer implications about everyday upper limb movement control for stroke survivors; function appeared to be prioritised over bimanual temporal synchrony or accuracy. For example, a task such as opening a jar with both limbs may be able to be completed quicker by using the unimpaired limb only; by holding the jar in between the knees and opening it using the unimpaired limb, such a strategy may not be making use of both limbs, but may be the most efficient for function. Furthermore, the theoretical and practical implications from findings from stroke survivors study offers insights into possible lack of awareness following stroke, a deficit that could further be weakened through learned non-use as function is prioritised over complete rehabilitation of the unimpaired limb due to the chronic nature of stroke. Another point of interest is that the stroke survivors in Chapter 5 study had relatively mild hemiparesis, yet the behaviour observed appeared to be unintuitive; with more severe hemiparesis of a limb likely to cause further detriment to inter-limb coupling and overall performance. A practical implication of the findings may be in applying the findings to aid upper limb rehabilitation interventions (Kantak et al., 2016, Kantak et al., 2017, Singh et al., 2018, Collins et al., 2018).

Strengths and potential limitations

Alongside the development of a robust paradigm to study visual control of upper limb movements, a particular strength of this thesis is that it presents the first study to do so in stroke survivors with mild hemiparesis. The developed paradigm's novel features ensure it is an excellent mode of research in the area and enabled precise and accurate capture of data whilst mitigating for factors which may have been viewed as limitations in previous studies. For instance, using a touch screen provided a naturalistic and more precise method to measure accuracy in reaching movements, rather than simply a hit or miss target design. Furthermore, the randomised equidistant movement of targets within trials ensured no learning effects would take place as task conditions were repeated. Another advantage of the set up was its relative ease of set up, which allowed the testing of individuals with sensory and motor impairments.

The experiment's set up in measurement of eye movements during unimanual and bimanual reaching was viable and robust for its intended use (to determine the direction in which participants gazed), and allowed computation of the proportion of gaze towards the target side(s) during reaching movements. However, a potential limitation as highlighted before (in Chapter 3) is the lack of spatial accuracy with using the EOG methodology to measure eye movements. Although we were able to measure the direction in which participants fixated their gaze, we are unable to dissociate whether the participant fixated their gaze towards their own limb or at the target. After the initial experiment had been set up and operating for some time, another research tool was made available in the lab; Eyelink 1000 Plus (https://www.sr-research.com/eyelink-1000-plus/) a video-based desktop eye tracker that has the capability to offer improvement to the paradigm. With video-based tracking of the eyeball at 2000 Hz, the system allows researchers to quantify spatial as well as temporal output from saccade behaviour, which would enhance the paradigm as it enables researchers to determine where the participant is foveating at high temporal and spatial precision. Interestingly, pilot work with this system strongly suggests that, for unimpaired individuals at least, participants make eye movements purely to the targets (i.e. not the hands).

Summary of future directions

Future research in visually guided upper limb reach movements, researchers should aim to consider using paradigms that are more applicable to real life; this will add to the current knowledge base and offer more ecological validity too. The spatial coupling between the two limbs may be considered alongside the temporal coupling for illuminating how the visuomotor system plans and executes gaze distribution within a trial, which would enable a more real world view of such tasks; for instance, when conducting a symmetrical bimanual task such as picking up an object, both limbs require *both* temporal and spatial synchrony. Findings on the attentional bias to the right limb could also be further explored for spatial synchrony between the limbs under covert and overt visual control; doing so would make the experimental task more closer to everyday activities as many daily life activities are performed under both covert and overt attentional control, and require both limbs to be in temporal as well as spatial synchrony.

For stroke survivors, the findings from Chapter 5 provided insights into the control and coordination between limbs when one limb is impaired. In addition to more Activities of Daily Living-based movements as suggested before, future research may consider exploring how the severity of hemiparesis affects upper limb control and involvement in bimanual tasks. For instance, stroke survivor participants could be sub-grouped by the severity of impairment; aside from the relationship between impairment and coordination between limbs in reaching movements. Such research would also offer insights into whether the severity of impairment has an impact on the observed lack of awareness of deficit.

Conclusions

In conclusion, this process of this thesis involved developing a robust experimental design to explore the visual control of unimanual and bimanual movements. The novel task was used to study upper limb movement behaviour in unimpaired as well as individuals with impairment, and showed key similarities and differences in control and coordination of movement under covert and overt visual attention. Under both attentional modes of control, small but reliable asynchronies between the limbs were driven by visual demands of bimanual movements. Furthermore, research on stroke survivors showed that the hemiparetic limb bore the cost of moving both limbs together under overt control, whilst also highlighting that a lack of awareness of deficit (anosognosia) may interfere in abilities to complete temporally coupled bimanual movements. Further research is suggested in tasks which are closer to daily life activities, so that implications have greater impacts for rehabilitation as well as offering more ecological generalizability.

References

ALBERTS, J. L., TRESILIAN, J. R. & STELMACH, G. E. 1998. The co-ordination and phasing of a bilateral prehension task - The influence of Parkinson's disease. *Brain,* 121**,** 725-742.

ALT MURPHY, M., WILLÉN, C. & SUNNERHAGEN, K. S. 2011. Kinematic variables quantifying upper-extremity performance after stroke during reaching and drinking from a glass. *Neurorehabil Neural Repair,* 25**,** 71-80.

BACHMANN, D., WEICHERT, F. & RINKENAUER, G. 2014. Evaluation of the leap motion controller as a new contact-free pointing device. *Sensors (Basel),* 15**,** 214-33.

BALAKRISHNAN, R. & HINCKLEY, K. 2000. Symmetric bimanual interaction. *Proceedings of the SIGCHI conference on Human Factors in Computing Systems.* The Hague, The Netherlands: Association for Computing Machinery.

BAREA NAVARRO, R., BOQUETE VÁZQUEZ, L. & LÓPEZ GUILLÉN, E. 2018. Chapter 16 - EOG-based wheelchair control. *In:* DIEZ, P. (ed.) *Smart Wheelchairs and Brain-Computer Interfaces.* Academic Press.

BARTHELEMY, S. & BOULINGUEZ, P. 2001. Manual reaction time asymmetries in human subjects: the role of movement planning and attention. *Neurosci Lett,* 315**,** 41-4.

BEETS, I., GOOIJERS, J., BOISGONTIER, M., PAUWELS, L., COXON, J., WITTENBERG, G. & SWINNEN, S. 2015. Reduced neural differentiation between feedback conditions after bimanual coordination training with and without augmented visual feedback. *Cerebral Cortex*.

BERNSTEIN, N. A. 1967. The co-ordination and regulation of movements.

BINGHAM, G. P., HUGHES, K. & MON-WILLIAMS, M. 2008. The coordination patterns observed when two hands reach-to-grasp separate objects. *Experimental Brain Research,* 184**,** 283-293.

BINSTED, G., CHUA, R., HELSEN, W. & ELLIOTT, D. 2001. Eye-hand coordination in goal-directed aiming. *Hum Mov Sci,* 20**,** 563-85.

BISIACH, E. & GEMINIANI, G. 1991. Anosognosia related to hemiplegia and hemianopia. *Awareness of deficit after brain injury: Clinical and theoretical issues.* New York, NY, US: Oxford University Press.

BLAIS, M., ELODIE, M., ALBARET, J.-M. & TALLET, J. 2014. Preservation of perceptual integration improves temporal stability of bimanual coordination in the elderly: An evidence of age-related brain plasticity. *Behavioural Brain Research*.

BLINCH, J., DOAN, J. B. & GONZALEZ, C. L. R. 2018. Complexity of movement preparation and the spatiotemporal coupling of bimanual reach-to-grasp movements. *Experimental Brain Research*.

BLOUIN, J., SARADJIAN, A. H., LEBAR, N., GUILLAUME, A. & MOUCHNINO, L. 2014. Opposed optimal strategies of weighting somatosensory inputs for planning reaching movements toward visual and proprioceptive targets. *J Neurophysiol,* 112**,** 2290-301.

BOESSENKOOL, J. J., NIJHOF, E.-J. & ERKELENS, C. J. 1999. Variability and correlations in bi-manual pointing movements. *Human Movement Science,* 18**,** 525-552.

BRADSHAW, J. L. & ROGERS, L. J. 1993. The evolution of lateral asymmetries, language, tool use, and intellect.

BRITTEN, L., COATS, R. O., ICHIYAMA, R. M., RAZA, W., JAMIL, F. & ASTILL, S. L. 2018. The effect of task symmetry on bimanual reach-to-grasp movements after cervical spinal cord injury. *Experimental Brain Research,* 236**,** 3101-3111.

BROWN, M., MARMOR, M., ZRENNER, E., BRIGELL, M. & BACH, M. 2006. ISCEV standard for clinical electro-oculography (EOG) 2006. *Documenta ophthalmologica,* 113**,** 205-212.

BRUTTINI, C., ESPOSTI, R., BOLZONI, F. & CAVALLARI, P. 2016. Higher Precision in Pointing Movements of the Preferred vs. Non-Preferred Hand Is Associated with an Earlier Occurrence of Anticipatory Postural Adjustments. *Front Hum Neurosci,* 10**,** 365.

BRUYN, J. L. & MASON, A. H. 2009. Temporal coordination during bimanual reach-to-grasp movements: the role of vision. *The Quarterly Journal of Experimental Psychology,* 62**,** 1328-42.

BUCKINGHAM, G. & CAREY, D. P. 2009. Rightward biases during bimanual reaching. *Experimental Brain Research,* 194**,** 197-206.

BUCKINGHAM, G. & CAREY, D. P. 2014. Attentional asymmetries - cause or consequence of human right handedness? *Frontiers in Psychology,* 5**,** 1587.

BUCKINGHAM, G., MAIN, J. C. & CAREY, D. P. 2011. Asymmetries in motor attention during a cued bimanual reaching task: left and right handers compared. *Cortex,* 47**,** 432-40.

CAREY, L. M. & MATYAS, T. A. 2011. Frequency of discriminative sensory loss in the hand after stroke in a rehabilitation setting. *J Rehabil Med,* 43**,** 257-63.

CARLTON, L. 1981a. Processing visual feedback information for movement control. *J Exp Psychol Hum Percept Perform,* 7**,** 1019-30.

CARLTON, L. 1981b. Visual information: The control of aiming movements. *The Quarterly Journal of Experimental Psychology Section A,* 33**,** 87-93.

CARRASCO, M. 2011. Visual attention: the past 25 years. *Vision Res,* 51**,** 1484-525.

CARSON, R. G. & SWINNEN, S. P. 2002. Coordination and movement pathology: models of structure and function. *Acta Psychol.(Amst),* 110**,** 357-364.

CASTIELLO, U. & BENNETT, K. M. 1997. The bilateral reach-to-grasp movement of Parkinson's disease subjects. *Brain,* 120 (Pt 4)**,** 593-604.

CASTIELLO, U., BENNETT, K. M. B. & STELMACH, G. E. 1993. The Bilateral Reach to Grasp Movement. *Behavioural Brain Research,* 56**,** 43-57.

CHEN, X. & DAVIS, J. 2002. Camera Placement Considering Occlusion for Robust Motion Capture. *Computer Graphics Laboratory, Stanford University, Tech. Rep,* 2.

COATS, R. O. & WANN, J. P. 2012. Reaching a better understanding of the control of bimanual movements in older adults. *PloS one,* 7.

COHN, R. 1951. Interaction in bilaterally simultaneous voluntary motor function. *A.M.A. Archives of Neurology & Psychiatry,* 65**,** 472-476.

COLLINS, K. C., KENNEDY, N. C., CLARK, A. & POMEROY, V. M. 2018. Kinematic Components of the Reach-to-Target Movement After Stroke for Focused Rehabilitation Interventions: Systematic Review and Meta-Analysis. *Frontiers in neurology,* 9**,** 472-472.

CORCOS, D. M. 1984. Two-Handed Movement Control. *Research Quarterly for Exercise and Sport,* 55**,** 117-122.

CUTTING, J. 1978. Study of anosognosia. *J Neurol Neurosurg Psychiatry,* 41**,** 548-55.

DALMAIJER, E. 2014. Is the low-cost EyeTribe eye tracker any good for research? : PeerJ Preprints.

DAVIS, A. M., BEATON, D., HUDAK, P., AMADIO, P., BOMBARDIER, C., COLE, D., HAWKER, G., KATZ, J., MAKELA, M. & MARX, R. 1999. Measuring disability of the upper extremity: a rationale supporting the use of a regional outcome measure. *Journal of Hand Therapy,* 12**,** 269-274.

DE HAAN, R., HORN, J., LIMBURG, M., VAN DER MEULEN, J. & BOSSUYT, P. 1993. A comparison of five stroke scales with measures of disability, handicap, and quality of life. *Stroke,* 24**,** 1178-1181.

DEJONG, S. L. & LANG, C. E. 2012. Comparison of Unilateral Versus Bilateral Upper Extremity Task Performance After Stroke. *Topics in Stroke Rehabilitation,* 19**,** 294-305.

DESMURGET, M., PÉLISSON, D., ROSSETTI, Y. & PRABLANC, C. 1998. From eye to hand: planning goal-directed movements. *Neuroscience & Biobehavioral Reviews,* 22**,** 761-788.

DICKSTEIN, R., HOCHERMAN, S., AMDOR, G. & PILLAR, T. 1993. Reaction and Movement Times in Patients With Hemiparesis for Unilateral and Bilateral Elbow Flexion. *Physical Therapy,* 73**,** 374-380.

DIEDRICHSEN, GRAFTON, S., ALBERT, N., HAZELTINE, E. & IVRY, R. B. 2006. Goal-Selection and Movement-Related Conflict during Bimanual Reaching Movements. *Cerebral Cortex,* 16**,** 1729-1738.

DIEDRICHSEN, J., NAMBISAN, R., KENNERLEY, S. W. & IVRY, R. B. 2004. Independent on-line control of the two hands during bimanual reaching. *European Journal of Neuroscience,* 19**,** 1643-1652.

DONCHYTS, G., BAART, F., DAM, A. & JAGERS, B. 2014. *Benefits of the use of natural user interfaces in water simulations*.

DUNCAN, J., HUMPHREYS, G. & WARD, R. 1997. Competitive brain activity in visual attention. *Current Opinion in Neurobiology,* 7**,** 255-261.

DURET, C., GROSMAIRE, A.-G. & KREBS, H. I. 2019. Robot-Assisted Therapy in Upper Extremity Hemiparesis: Overview of an Evidence-Based Approach. *Frontiers in neurology,* 10**,** 412-412.

FINDLAY, J. M. & GILCHRIST, I. D. 2003. *Active vision: The psychology of looking and seeing,* New York, NY, US, Oxford University Press.

FINGER, S. 2004. Paul Broca (1824–1880). *Journal of Neurology,* 251**,** 769-770.

FISK, J. & GOODALE, M. 1985. The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. *Experimental brain research,* 60**,** 159-178.

FITTS, P. M. 1954. The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement. *Journal of Experimental Psychology,* 47**,** 381-391.

FOWLER, B., DUCK, T., MOSHER, M. & MATHIESON, B. 1991. The coordination of bimanual aiming movements: evidence for progressive desynchronization. *The Quarterly Journal of Experimental Psychology,* 43**,** 205-221.

FRANZ, E. A. 2003. Bimanual action representation: A window to human evolution. *Taking action: Cognitive neuroscience perspectives on intentional acts.***,** 259-88.

FRANZ, E. A. & JOHNSTON-FREY, S. 2003. Taking action: Cognitive neuroscience perspectives on the problem of intentional acts.

FRANZ, E. A., ZELAZNIK, H. N. & MCCABE, G. 1991. Spatial topological constraints in a bimanual task. *Acta Psychol.(Amst),* 77**,** 137-151.

FRITH, C. D., BLAKEMORE, S. J. & WOLPERT, D. M. 2000. Abnormalities in the awareness and control of action. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences,* 355**,** 1771-1788.

GARBARINI, RABUFFETTI, M., PIEDIMONTE, A., PIA, L., FERRARIN, M., FRASSINETTI, F., GINDRI, P., CANTAGALLO, A., DRIVER, J. & BERTI, A. 2012a. 'Moving' a paralysed hand: Bimanual coupling effect in patients with anosognosia for hemiplegia. *Brain,* 135**,** 1486-1497.

GARBARINI, RABUFFETTI, M., PIEDIMONTE, A., PIA, L., FERRARIN, M., FRASSINETTI, F., GINDRI, P., CANTAGALLO, A., DRIVER, J. & BERTI, A. 2012b. 'Moving' a paralysed hand: bimanual coupling effect in patients with anosognosia for hemiplegia. *Brain,* 135**,** 1486-1497.

GARBARINI, F. & PIA, L. 2013. Bimanual coupling paradigm as an effective tool to investigate productive behaviors in motor and body awareness impairments. *Front Hum Neurosci,* 7**,** 737.

GARBARINI, F., PIEDIMONTE, A., DOTTA, M., PIA, L. & BERTI, A. 2013. Dissociations and similarities in motor intention and motor awareness: the case of anosognosia for hemiplegia and motor neglect. *J.Neurol.Neurosurg.Psychiatry,* 84**,** 416-419.

GLADSTONE, D. J., DANELLS, C. J. & BLACK, S. E. 2002. The fugl-meyer assessment of motor recovery after stroke: a critical review of its measurement properties. *Neurorehabil Neural Repair,* 16**,** 232-40.

GOBLE, COXON, J., IMPE, A., VOS, J., WENDEROTH, N. & SWINNEN, S. 2010. The neural control of bimanual movements in the elderly: Brain regions exhibiting age-related increases in activity, frequency-induced neural modulation, and task-specific compensatory recruitment. *Human brain mapping,* 31**,** 1281-95.

GOBLE, D. J. & BROWN, S. H. 2008a. The biological and behavioral basis of upper limb asymmetries in sensorimotor performance. *Neurosci Biobehav Rev,* 32**,** 598-610.

GOBLE, D. J. & BROWN, S. H. 2008b. Upper limb asymmetries in the matching of proprioceptive versus visual targets. *Journal of Neurophysiology,* 99**,** 3063-74.

HAALAND, K. Y., MUTHA, P. K., RINEHART, J. K., DANIELS, M., CUSHNYR, B. & ADAIR, J. C. 2012. Relationship between arm usage and instrumental activities of daily living after unilateral stroke. *Arch Phys Med Rehabil,* 93**,** 1957-62.

HAYHOE, M. & BALLARD, D. 2005. Eye movements in natural behavior. *Trends in cognitive sciences,* 9**,** 188-194.

HELLSTRÖM, K., LINDMARK, B., WAHLBERG, B. & FUGL-MEYER, A. R. 2003. Self-efficacy in relation to impairments and activities of daily living disability in elderly patients with stroke: a prospective investigation. *J Rehabil Med,* 35**,** 202-7.

HESSE, C., NAKAGAWA, T. T. & DEUBEL, H. 2010. Bimanual movement control is moderated by fixation strategies. *Experimental Brain Research,* 202**,** 837-850.

HONDA, H. 1982. Rightward superiority of eye movements in a bimanual aiming task. *The Quarterly Journal of Experimental Psychology,* 34**,** 499-513.

JACKSON, G. M., GERMAN, K. & PEACOCK, K. 2002a. Functional coupling between the limbs during bimanual reach-to-grasp movements. *Human Movement Science,* 21**,** 317-333.

JACKSON, G. M., JACKSON, S. R., HUSAIN, M., HARVEY, M., KRAMER, T. & DOW, L. 2000. The coordination of bimanual prehension movements in a centrally deafferented patient. *Brain,* 123 (Pt 2)**,** 380-393.

JACKSON, G. M., JACKSON, S. R. & KRITIKOS, A. 1999. Attention for action: coordinating bimanual reach-to-grasp movements. *British Journal of Psychology,* 90**,** 247-270.

JACKSON, G. M., JACKSON, S. R., NEWPORT, R. & HARVEY, M. 2002b. Co-ordination of bimanual movements in a centrally deafferented patient executing open loop reach-to-grasp movements. *Acta Psychol.(Amst),* 110**,** 231-246.

JEANNEROD, M. 1981. Intersegmental coordination during reaching at natural visual objects. *In:* LONG, J. & BADDELEY, A. (eds.) *Attention and Performance IX.* Hillsdale: Lawrence Erlbaum Associates.

JEANNEROD, M. 1984. The timing of natural prehension movements. *J.Mot.Behav.,* 16**,** 235-254.

JEANNEROD, M., MICHEL, F. & PRABLANC, C. 1984. The control of hand movements in a case of hemianaesthesia following a parietal lesion. *Brain,* 107 (Pt 3)**,** 899-920.

JOHANSSON, R. S., WESTLING, G., BÄCKSTRÖM, A. & FLANAGAN, J. R. 2001. Eye-hand coordination in object manipulation. *J Neurosci,* 21**,** 6917-32.

KANTAK, S., JAX, S. & WITTENBERG, G. 2017. Bimanual coordination: A missing piece of arm rehabilitation after stroke. *Restor Neurol Neurosci,* 35**,** 347-364.

KANTAK, S., MCGRATH, R. & ZAHEDI, N. 2016. Goal conceptualization and symmetry of arm movements affect bimanual coordination in individuals after stroke. *Neurosci Lett,* 626**,** 86-93.

KELSO, PUTNAM, C. A. & GOODMAN, D. 1983. On the space-time structure of human interlimb co-ordination. *Quarterly Journal of Experimental Psychology,* 35 Pt 2**,** 347-375.

KELSO, SOUTHARD, D. L. & GOODMAN, D. 1979. On the nature of human interlimb coordination. *Science,* 203**,** 1029-1031.

KILBREATH, S. L. & HEARD, R. C. 2005. Frequency of hand use in healthy older persons. *Aust J Physiother,* 51**,** 119-22.

KRAKAUER, J. & CARMICHAEL, S. T. 2017. *Broken Movement: The Neurobiology of Motor Recovery after Stroke*.

KREHBIEL, L. M., KANG, N. & CAURAUGH, J. H. 2017. Age-related differences in bimanual movements: A systematic review and meta-analysis. *Exp Gerontol,* 98**,** 199-206.

LAI, C. H., SUNG, W. H., CHIANG, S. L., LU, L. H., LIN, C. H., TUNG, Y. C. & LIN, C. H. 2019. Bimanual coordination deficits in hands following stroke and their relationship with motor and functional performance. *J Neuroeng Rehabil,* 16**,** 101.

LAND, M. F. & HAYHOE, M. 2001. In what ways do eye movements contribute to everyday activities? *Vision Res,* 41**,** 3559-65.

LAWRENCE, E. S., COSHALL, C., DUNDAS, R., STEWART, J., RUDD, A. G., HOWARD, R. & WOLFE, C. D. 2001a. Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population. *Stroke,* 32**,** 1279-84.

LAWRENCE, E. S., COSHALL, C., DUNDAS, R., STEWART, J., RUDD, A. G., HOWARD, R. & WOLFE, C. D. 2001b. Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population. *Stroke,* 32**,** 1279-1284.

LEE, T., WISHART, L. & MURDOCH, J. 2002. Aging, Attention, and Bimanual Coordination. *Canadian Journal on Aging / La Revue canadienne du vieillissement,* 21.

LIU, W., WHITALL, J. & KEPPLE, T. M. 2013. Multi-joint coordination of functional arm reaching: induced position analysis. *Journal of applied biomechanics,* 29**,** 235-240.

LOEHRER, P., NETTERSHEIM, F., JUNG, F., WEBER, I., HUBER, C., DEMBEK, T., PELZER, E., FINK, G., TITTGEMEYER, M. & TIMMERMANN, L. 2016. Ageing changes effective connectivity of motor networks during bimanual finger coordination. *NeuroImage,* 143.

MAES, C., GOOIJERS, J., ORBAN, J., SWINNEN, S. & BOISGONTIER, M. 2017. Two hands, one brain, and aging. *Neuroscience & Biobehavioral Reviews,* 75**,** 234-256.

MAHONEY, F. & BARTHEL, D. 1965. Functional evaluation: the Barthel index. *Md State Med.J.,* 14**,** 61-65.

MANI, S., MUTHA, P. K., PRZYBYLA, A., HAALAND, K. Y., GOOD, D. C. & SAINBURG, R. L. 2013. Contralesional motor deficits after unilateral stroke reflect hemisphere-specific control mechanisms. *Brain,* 136**,** 1288-303.

MARTENIUK, R. G., MACKENZIE, C. L. & BABA, D. M. 1984. Bimanual Movement Control: Information Processing and Interaction Effects. *The Quarterly Journal of Experimental Psychology,* 36**,** 335-365.

MCCREA, P. H. & ENG, J. J. 2005. Consequences of increased neuromotor noise for reaching movements in persons with stroke. *Exp Brain Res,* 162**,** 70-7.

MEADMORE, K. L., EXELL, T. A., BURRIDGE, J. H., HUGHES, A.-M., FREEMAN, C. T. & BENSON, V. 2018a. Upper limb and eye movement coordination during reaching tasks in people with stroke. *Disability and Rehabilitation,* 40**,** 2424-2432.

MEADMORE, K. L., EXELL, T. A., BURRIDGE, J. H., HUGHES, A. M., FREEMAN, C. T. & BENSON, V. 2018b. Upper limb and eye movement coordination during reaching tasks in people with stroke. *Disabil Rehabil,* 40**,** 2424-2432.

MESSIER, S., BOURBONNAIS, D., DESROSIERS, J. & ROY, Y. 2006. Kinematic analysis of upper limbs and trunk movement during bilateral movement after stroke. *Arch Phys Med Rehabil,* 87**,** 1463-70.

MILLER, K. A. & SMYTH, M. M. 2012. Asynchrony in discrete bimanual aiming: evidence for visual strategies of coordination. *The Quarterly Journal of Experimental Psychology,* 65**,** 1911-26.

NEWELL, K. M., VAILLANCOURT, D. E. & SOSNOFF, J. J. 2006. Aging, complexity, and motor performance. *Handbook of the psychology of aging.* Elsevier.

NIECHWIEJ-SZWEDO, E., GONZALEZ, D., NOUREDANESH, M. & TUNG, J. 2018. Evaluation of the Leap Motion Controller during the performance of visually-guided upper limb movements. *PLOS ONE,* 13**,** e0193639.

NOWAK, D. 2008. The impact of stroke on the performance of grasping: Usefulness of kinetic and kinematic motion analysis. *Neuroscience and biobehavioral reviews,* 32**,** 1439-50.

OBHI, S. S. 2004. Bimanual Coordination: An Unbalanced Field of Research. 8**,** 111.

OLDFIELD, R. C. 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia,* 9**,** 97-113.

OOMS, K., DUPONT, L., LAPON, L. & POPELKA, S. 2015. - Accuracy and precision of fixation locations recorded with the low-cost Eye Tribe tracker in different experimental set-ups. - 8.

PERENIN, M. T. & JEANNEROD, M. 1978. Visual function within the hemianopic field following early cerebral hemidecortication in man--I. Spatial localization. *Neuropsychologia,* 16**,** 1-13.

PETERS, M. 1981. Attentional asymmetries during concurrent bimanual performance. *The Quarterly Journal of Experimental Psychology,* 33**,** 95-103.

POMEROY, V. & TALLIS, R. 2002. Restoring movement and functional ability after stroke: Now and the future. *Physiotherapy,* 88**,** 3-17.

POSNER, M., NISSEN, M. & OGDEN, W. 1978. Attended and unattended processing modes: The role of set for spatial location. *Modes of Perceiving and Processing Information,* 137.

POSNER, M. I. 1980. Orienting of attention. *Q.J.Exp.Psychol.,* 32**,** 3-25.

PUEO, B. & JIMENEZ-OLMEDO, J. 2017. Application of motion capture technology for sport performance analysis. *Retos: nuevas tendencias en educación física, deporte y recreación,* 2017**,** 241-247.

PUNT, T. D., RIDDOCH, M. J. & HUMPHREYS, G. W. 2005a. Bimanual coordination and perceptual grouping in a patient with motor neglect. *Cognitive Neuropsychology,* 22**,** 795-815.

PUNT, T. D., RIDDOCH, M. J. & HUMPHREYS, G. W. 2005b. Don't think twice, it's all right-contralesional dependency for bimanual prehension movements. *Neuropsychologia,* 43**,** 1547-1558.

RAMAT, S., LEIGH, R., ZEE, D. & OPTICAN, L. M. 2007. What clinical disorders tell us about the neural control of saccadic eye movements. *American Journal of Ophthalmology,* 143**,** 543.

RAYNOWSKA, J., RIZZO, J.-R., RUCKER, J. C., DAI, W., BIRKEMEIER, J., HERSHOWITZ, J., SELESNICK, I., BALCER, L. J., GALETTA, S. L. & HUDSON, T. 2018. Validity of low-resolution eye-tracking to assess eye movements during a rapid number naming task: performance of the eyetribe eye tracker. *Brain injury,* 32**,** 200-208.

RICE, M. S. & NEWELL, K. M. 2004. Upper-extremity interlimb coupling in persons with left hemiplegia due to stroke. *Arch.Phys.Med.Rehabil.,* 85**,** 629-634.

RIEK, S., TRESILIAN, J. R., MON-WILLIAMS, M., COPPARD, V. L. & CARSON, R. G. 2003. Bimanual aiming and overt attention: one law for two hands. *Experimental Brain Research,* 153**,** 59-75.

ROSE, D. K. & WINSTEIN, C. J. 2005. The co-ordination of bimanual rapid aiming movements following stroke. *Clin Rehabil,* 19**,** 452-62.

ROY, E. A. & ELLIOTT, D. 1986. Manual asymmetries in visually directed aiming. *Can J Psychol,* 40**,** 109-21.

ROY, E. A., ROY, E. A. & ELLIOTT, D. 1989. Manual Asymmetries in Aimed Movements. *The Quarterly Journal of Experimental Psychology,* 41**,** 501-516.

SAINBURG, R. L. 2002. Evidence for a dynamic-dominance hypothesis of handedness. *Experimental Brain Research,* 142**,** 241-58.

SAINBURG, R. L. & KALAKANIS, D. 2000. Differences in control of limb dynamics during dominant and nondominant arm reaching. *J Neurophysiol,* 83**,** 2661-75.

SAINBURG, R. L. & SCHAEFER, S. Y. 2004. Interlimb differences in control of movement extent. *J Neurophysiol,* 92**,** 1374-83.

SARLEGNA, F. R. & SAINBURG, R. L. 2009. The roles of vision and proprioception in the planning of reaching movements. *Adv Exp Med Biol,* 629**,** 317-35.

SCHAEFER, S. Y., HAALAND, K. Y. & SAINBURG, R. L. 2007. Ipsilesional motor deficits following stroke reflect hemispheric specializations for movement control. *Brain,* 130**,** 2146-58.

SCHERDER, E., DEKKER, W. & EGGERMONT, L. 2008. Higher-level hand motor function in aging and (preclinical) dementia: its relationship with (instrumental) activities of daily life--a mini-review. *Gerontology,* 54**,** 333-41.

SCHMIDT, R. A. 1975. A schema theory of discrete motor skill learning. *Psychological Review,* 82**,** 225-260.

SEMRAU, J., HERTER, T., SCOTT, S. & DUKELOW, S. 2013. Robotic Identification of Kinesthetic Deficits After Stroke. *Stroke; a journal of cerebral circulation,* 44.

SHERWOOD, D. E. 1991. Distance and location assimilation effects in rapid bimanual movement. *Res Q Exerc Sport,* 62**,** 302-8.

SHERWOOD, D. E. 2014. Aiming accuracy in preferred and non-preferred limbs: implications for programing models of motor control. *Frontiers in psychology,* 5**,** 1236.

SINGH, T., PERRY, C. M., FRITZ, S. L., FRIDRIKSSON, J. & HERTER, T. M. 2018. Eye Movements Interfere With Limb Motor Control in Stroke Survivors. *Neurorehabil Neural Repair,* 32**,** 724-734.

SOBER, S. J. & SABES, P. N. 2005. Flexible strategies for sensory integration during motor planning. *Nat Neurosci,* 8**,** 490-7.

SOSNOFF, J. J. & NEWELL, K. M. 2006. Are age-related increases in force variability due to decrements in strength? *Exp Brain Res,* 174**,** 86-94.

SRINIVASAN, D. & MARTIN, B. J. 2010. Eye-hand coordination of symmetric bimanual reaching tasks: temporal aspects. *Experimental Brain Research,* 203**,** 391-405.

STELMACH, G. E., GOGGIN, N. L. & AMRHEIN, P. C. 1988. Aging and the restructuring of precued movements. *Psychol Aging,* 3**,** 151-7.

STEWART, J. C., LEWTHWAITE, R., ROCKTASHEL, J. & WINSTEIN, C. J. 2019. Self-efficacy and Reach Performance in Individuals With Mild Motor Impairment Due to Stroke. *Neurorehabil Neural Repair,* 33**,** 319-328.

SWINNEN 2002. Intermanual coordination: from behavioural principles to neural-network interactions. *Nat.Rev.Neurosci.,* 3**,** 348-359.

SWINNEN, VERSCHUEREN, S., BOGAERTS, H., DOUNSKAIA, N., LEE, T., STELMACH, G. & SERRIEN, D. 1998. Age-related deficits in motor learning and differences in feedback processing during the production of a bimanual coordination pattern. *Cognitive Neuropsychology,* 15**,** 439-466.

TAUB, E., USWATTE, G., MARK, V. W. & MORRIS, D. M. 2006. The learned nonuse phenomenon: implications for rehabilitation. *Eura Medicophys,* 42**,** 241-56.

TROMBLY, C. A. 1993. Observations of improvement of reaching in five subjects with left hemiparesis. *J Neurol Neurosurg Psychiatry,* 56**,** 40-5.

TURVEY, M. T. Preliminaries to a theory of action with reference to vision. 1977.

VEERBEEK, J. M., KWAKKEL, G., VAN WEGEN, E. E., KET, J. C. & HEYMANS, M. W. 2011. Early prediction of outcome of activities of daily living after stroke: a systematic review. *Stroke,* 42**,** 1482-8.

WADE, D. T., LANGTON-HEWER, R., WOOD, V. A., SKILBECK, C. E. & ISMAIL, H. M. 1983. The hemiplegic arm after stroke: measurement and recovery. *J.Neurol.Neurosurg.Psychiatry,* 46**,** 521-524.

WARD, N. S., NEWTON, J. M., SWAYNE, O. B., LEE, L., THOMPSON, A. J., GREENWOOD, R. J., ROTHWELL, J. C. & FRACKOWIAK, R. S. 2006. Motor system activation after subcortical stroke depends on corticospinal system integrity. *Brain,* 129**,** 809-19.

WELSH, T. N., HIGGINS, L. & ELLIOTT, D. 2007. Are there age-related differences in learning to optimize speed, accuracy, and energy expenditure? *Human Movement Science,* 26**,** 892-912.

WIESENDANGER, M., KAZENNIKOV, O., PERRIG, S. & KALUZNY, P. 1996. Two hands—one action: The problem of bimanual coordination. *Hand and brain: The neurophysiology and psychology of hand movements.* San Diego, CA, US: Academic Press.

WING, A. & BEEK, P. 2004. Motion analysis: a joint centenary. *Hum Mov Sci,* 23**,** iii-iv.

WINSTEIN, C. J., WOLF, S. L., DROMERICK, A. W., LANE, C. J., NELSEN, M. A., LEWTHWAITE, R., CEN, S. Y. & AZEN, S. P. 2016. Effect of a Task-Oriented Rehabilitation Program on Upper Extremity Recovery Following Motor Stroke: The ICARE Randomized Clinical Trial. *Jama,* 315**,** 571-81.

WOODWORTH, R. S. 1899. Accuracy of voluntary movement. *The Psychological Review: Monograph Supplements,* 3**,** i-114.

WU, TROMBLY, C. A., LIN, K. & TICKLE-DEGNEN, L. 2000. A kinematic study of contextual effects on reaching performance in persons with and without stroke: influences of object availability. *Arch Phys Med Rehabil,* 81**,** 95-101.

WU, C. Y., CHEN, C. L., TANG, S. F., LIN, K. C. & HUANG, Y. Y. 2007. Kinematic and clinical analyses of upper-extremity movements after constraint-induced movement therapy in patients with stroke: a randomized controlled trial. *Arch Phys Med Rehabil,* 88**,** 964-70.

WU, C. Y., CHOU, S. H., KUO, M. Y., CHEN, C. L., LU, T. W. & FU, Y. C. 2008. Effects of object size on intralimb and interlimb coordination during a bimanual prehension task in patients with left cerebral vascular accidents. *Motor Control,* 12**,** 296-310.

ZUOZA, A., ALBERTAS, S., MICKEVICIENE, D., GUTNIK, B., ZOUZENE, D., PENCHEV, B. & PENCHEVA, S. 2009. Behavior of dominant and non dominant arms during ballistic protractive target-directed movements. *Fiziologiia cheloveka,* 35**,** 62-70.