BIMANUAL COORDINATION AND MIRROR VISUAL FEEDBACK:

IMPLICATIONS FOR MIRROR THERAPY

By

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Thesis summary

Most movements in daily life are performed with both hands. Both hands may do the same movement at the same time, or they may play different roles in demonstrating bimanual coordination to achieve the task. Stroke patients show abnormal bimanual coordination due to motor impairment. Traditionally, strategies of practising unimanual tasks with the impaired limb of stroke patients have been adopted to improve motor impairment. However, training with both hands simultaneously has been proposed as a more effective training strategy. Simultaneous symmetrical movement of both hands can benefit from an interlimb coupling effect, in which the movement of one hand impacts the movement of the other. In other words, bimanual training for stroke patients may improve movement deficits in the affected limb and help restore bimanual coordination. A mirror has been suggested as a device that may enhance the effect of bilateral training.

During mirror therapy, a mirror is positioned perpendicularly between both hands by placing the affected limb behind the mirror. Patients are instructed to move the unseen affected limb as much as possible while watching the movement of the unaffected limb reflected in the mirror. This promising intervention improves motor impairment and motor function in hemiparetic stroke patients. However, procedures used in multiple clinical studies and in practice vary considerably, and the underlying mechanism(s) that underpin mirror therapy are not known. Since the main purpose of mirror therapy is to improve the motor function of the unseen affected hand, this thesis aimed to contribute to our understanding of mirror therapy by examining the movement of the unseen hand that occurs during mirror visual feedback.

This thesis reports experiments that carefully examined bimanual movements for both unimpaired individuals and hemiparetic stroke patients under mirror visual feedback conditions. In the initial experiments (Chapter 2), the marked positional drift of the unseen limb (the limb behind the mirror) was highlighted when unimpaired individuals made continuous bimanual circle-drawing movements with mirror visual feedback. It became apparent that one might be able to examine an individual's ownership and agency over the illusory limb from moment to moment by identifying whether the movements of the unseen limb were modified in response to visual feedback created by the seen limb. A subsequent experiment and novel analytical approach in Chapter 3 addressed this issue. Chapter 4 applied the knowledge and techniques learned from the previous chapters in examining bimanual movements in a small number of stroke patients. Recent research suggests specific parameters (e.g., using a large mirror, not using objects) that may contribute to the optimal effectiveness of mirror therapy for stroke patients. In the final experimental chapter, the impact of modifying these parameters on the illusory limb as indicated by subjective ratings was explored in unimpaired participants. A comprehensive summary of the experiments and a general discussion of theoretical and clinical implications and future directions are presented in Chapter 6.

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Chapter 1. General introduction

Abstract

Individuals with stroke have abnormal bimanual coordination due to upper limb paresis. Bilateral training produces an interlimb coupling effect, which is advantageous for hemiparetic limb rehabilitation. Mirror therapy with bimanual execution is one form of bilateral training shown to improve the motor function of the hemiparetic limb. However, mirror therapy is implemented in different ways, and the mechanism(s) underpinning its effectiveness remains unknown. Studies of bimanual coordination with mirror visual feedback show an enhancement of the spatial coupling effect, leading to the notion that the intervention can affect the motor output of the unseen hand. However, the movement of the unseen hand during mirror visual feedback has yet to be thoroughly investigated. Therefore, the goal of this thesis was to investigate the movement of the unseen hand during mirror visual feedback based on bimanual coordination research. This chapter introduces the background of mirror therapy, clinical trials and findings, and associated motor control studies in detail, as well as the motivation for exploring the unseen hand.

Background

Humans make hundreds of harmonious movements with both hands every day. Even simple tasks call for the coordinated use of both hands, while skilled tasks require the most effective and collaborative use of both hands (Kilbreath & Heard, 2005). These movements are not apparent in infancy; only extremely primitive actions are feasible in the early years, and even simple coordinated activities are rare. Along with physical and mental development, more complicated movements become conceivable, as do advanced movements through constant practice and learning. When reaching adulthood, humans can typically carry out elaborate bimanual coordinated movements with ease and minimal effort. (Corbetta, 1996).

Displaying appropriate coordinated movements is a sign of normal development. This turns into a standard for evaluating normal motor control and an indication of an intact neuromuscular system. Abnormal coordinated movements may indicate an insult to the central nervous system, such as a stroke (McCombe Waller & Whitall, 2008). Following a stroke, signs of impaired bilateral function include impaired bilateral arm swing (Ustinova et al., 2006), slowed or disjointed bilateral reaching (McCombe Waller et al., 2008; Peters, 1977), and increased variability and discoordination in bilateral finger movements for typing (McCombe Waller & Whitall, 2004).

Bilateral training

Historically, rehabilitation for the hemiparetic arm following a stroke focused on practising unimanual tasks, and if this proves difficult, the nonparetic limb was introduced to assist the movement. However, training with both hands moving simultaneously has been proposed as a more beneficial method for the training (McCombe Waller & Whitall, 2008). The resulting interlimb coupling effect is thought to form the therapeutic basis for the bilateral training (McCombe Waller & Whitall, 2008). Interlimb coupling occurs when both arms move simultaneously, and one arm's movement affects the other arm's movement. Even if each arm executes a different task, the output of one arm reflects the movement of the opposite arm (Franz et al., 1991). Previous studies have reported an immediate and positive coupling effect due to bilateral training in individuals with hemiparetic stroke (Cauraugh et al., 2010).

Harris-Love et al. (2005) demonstrated temporal coupling in bilateral movements of stroke patients. Chronic stroke patients were asked to perform a unilateral or bilateral reaching task, and the kinematics of both hands were examined. When reaching unilaterally, values for velocity and peak acceleration were lower for the paretic limb than those of the nonparetic limb; however, when reaching bilaterally, the movement of the paretic limb enhanced compared with unilateral movements. Comparing only the movements of the paretic limb, bilateral movements had higher peak acceleration and velocity than unilateral movements.

Waller et al. (2006) demonstrated that the temporal coupling effect in hemiparetic patients was stronger when both hands moved simultaneously rather than sequentially. McCombe Waller et al. (2008) reported not only temporal but also a spatial contribution linked to bilateral training in stroke patients. The paretic limb was shown to move with a smoother trajectory when reaching following bilateral training than after unilateral training. In addition to the reaching task, an interlimb coupling effect was also reported in single joint movements such as the elbow (Cunningham et al., 2002; Dickstein et al., 1993; Rice & Newell, 2001, 2004) as well as other more complex multi-joint movements, for example, circle drawing (Lewis & Byblow, 2004).

With growing interest in bimanual training, various associated methods have been introduced with some degree of success (Stoykov & Corcos, 2009). For example, bilateral training has been facilitated using a device with rhythmic auditory cueing (e.g., BATRAC) (Whitall et al., 2000), a robotic device (Hesse et al., 2005) and a device supporting symmetrical movement (e.g., the Rocker) (van Delden et al., 2012). The use of such approaches is constrained for many by the expense of related equipment and challenging accessibility for novices. By comparison, mirror therapy may be considered a far more accessible method of bimanual training for stroke patients and is substantially less expensive (Yavuzer et al., 2008).

Mirror therapy

Mirror therapy is considered to enhance the body schema and overcome sensory deficits on the affected side by replacing the perceived position of the affected limb with visual feedback from the mirror of the unaffected side. As suggested by Ramachandran et al. (1995), the mirror is placed in the midsagittal plane of the table, between the patient's arms reflecting the unaffected limb, and the patient is instructed to gaze at the hand in the mirror. Individuals then perceive the unseen affected limb, making symmetrical bimanual movements by looking at the hand in the mirror (Rothgangel & Braun, 2013).

Before it was proposed for stroke patients, the mirror-based approach was first proposed for amputees (Ramachandran et al., 1995). Amputees often suffer painful involuntary clenching spasms from their phantom hands. In such circumstances, the motor command signal from the premotor and motor cortex to clench is normally damped and controlled by the proprioception feedback (Ramachandran & Hirstein, 1998). However, because the amputee's hand is missing, feedback is also missing, and the signal for the motor command is amplified, which may be the cause of the clenching spasms (Ramachandran & Altschuler, 2009; Ramachandran & Rogers-Ramachandran, 1996). It was also speculated that the phantom limb's spasms could not be controlled after amputation due to 'learned paralysis' of the affected arm prior to surgery. Observing an immobilised arm before surgery despite attempts at volitional movement could be interpreted as contradictory information being stamped on the neural circuitry (Ramachandran, 1993, 1994).

Some amputees report pain relief while observing normal hand movements reflected in mirrors superimposed on phantom limbs (Ramachandran & Rogers-Ramachandran, 1996). The mirror reflection of the normal hand allows the amputee to perceive movement from the non-existent arm. This gives the impression that the phantom arm's movement is being voluntarily controlled. Through this experience, the mirror is thought to play a beneficial role in unlearning the learned paralysis of the non-existent arm and relieving pain caused by spasms. Subsequent clinical studies have also shown that mirror therapy is effective for phantom limb pain (Foell et al., 2014; Seidel et al., 2009). The success of mirror therapy for phantom limb pain has led to its application to other neurological patients, such as complex regional pain syndrome (Cacchio et al., 2009; Karmarkar & Lieberman, 2006), hemiparesis following cerebral palsy (Feltham et al., 2010), and stroke (Thieme et al., 2018).

Mirror therapy for stroke

Altschuler et al. (1999) initially suggested using mirror therapy for stroke patients in a manner similar to how it is used on amputees. Nine patients with chronic stroke trained their upper limbs using either a transparent plastic sheet or a mirror (45 x 60cm) for four weeks before switching to another treatment for another four weeks. The intervention was carried out twice a day for 15 minutes, six days a week, for a total of eight weeks. During the intervention, patients were instructed to move both hands at the same time and to move the affected hand as much as possible. When using a mirror, the gaze was instructed to focus on the image in the mirror; and while using the transparent plastic sheet, to look at the affected hand beyond the plastic. Patients reported preferring looking in the mirror to using transparent plastic, and their movements (range of motion, speed, and accuracy) were found to be significantly improved with the mirror. This initial study showed that bimanual training with a mirror image could improve movement more than directly looking at the affected limb. From a neurophysiological standpoint, the use of a mirror was thought to contribute to premotor cortex recruitment leading to improved bilateral movement and enhancing motor rehabilitation.

Given the mirror's potential effects on stroke patients, studies of mirror therapy for stroke patients have received substantial attention. Mirror therapy has been used as an intervention in numerous randomised controlled trials for stroke survivors, and a subsequent systematic review of these trials (including meta-analysis) has clearly shown the intervention to be effective in improving motor function (Thieme et al., 2018).

Yavuzer et al. (2008) compared bilateral mirror therapy with a sham mirror therapy control group. They recruited forty subacute stroke patients and divided them into two groups to examine the effects of mirror therapy. Patients received thirty minutes of intervention in addition to conventional rehabilitation five times per week for four weeks. During mirror therapy, the subjects were instructed to perform wrist and finger flexion/extension movements while looking at their hand in the mirror (35×35cm). The control group was asked to complete the same task while looking at an opaque screen. As in the initial protocol, patients were instructed to move both hands at the same time. After four weeks of intervention, the mirror group improved their motor impairment (Brunnstrom stages for the hand and upper extremity) as well as their motor function (FIM self-care score) more than the control group.

Dohle et al. (2009) showed that mirror therapy could also be effective in acute stroke patients. The detailed method appears to have slightly deviated from Yavuzer's protocol because the participating patients had severe hemiparesis. Patients were randomly assigned to either the mirror or control groups, and the intervention lasted for six weeks, 30 minutes per day, five times per week. The control group was instructed to look directly at the affected hand, which was not obscured from view during the intervention. When performing the task, the affected hand was instructed to move as much as possible, but the movements were asked differently to the patients depending on their functional level. The mirror group demonstrated the improved function of the distal plegic limb. And it has also been shown to improve sensory and attention deficits.

Michielsen et al. (2011)'s study was conducted for chronic stroke patients in the same manner as Dohle et al. (2009)'s detailed method. However, the intervention was carried out at home, with patients receiving weekly supervision from a physiotherapist. Mirrors were found to improve motor impairment, and brain imaging revealed activation of the primary motor cortex in the affected hemisphere.

Arya et al. (2015) demonstrated that simply observing the movement of the seen hand with a mirror while not moving the affected unseen hand can also be effective during mirror therapy. Patients were instructed to perform unimanual execution, in which only the seen unaffected hand moves, rather than bimanual execution. The less-affected limb in front of the mirror box (24 × 18 × 14 inches) was instructed to make task-based movements (such as drinking water, cleaning the table, and picking up paper clips). Even when the unseen affected hand is not instructed to move together, the use of a mirror has been shown to improve motor recovery of the affected limb.

As can be seen from the four representative RCTs above, mirror therapy improved motor function and motor impairment in stroke patients (Hartman & Altschuler, 2016). However, the method of applying mirror therapy varies from study to study, and the fact that the mechanism is still unknown threatens the effectiveness of mirror therapy (Thieme et al., 2018).

A recent meta-analysis revealed that the effectiveness of mirror therapy appears to be dependent on the therapeutic protocol employed (Morkisch et al., 2019). Mirror therapy was found to be more effective when using a large mirror (larger than 50*40cm), *unilateral* movement execution, and no object manipulation. This result appears to provide general guidance on the optimal therapy protocol that should be followed, though in the absence of a clear rationale as to *why* these conditions are optimal also seems somewhat unsatisfactory.

Additionally, given the heterogeneity of stroke patients, it may be practically challenging to avoid the use of multiple protocols. Therefore, the effect of parameters on mirror therapy necessitates an understanding of the underlying mechanism.

Some neurophysiological studies shed some light on the concept of mirror therapy. Mirror therapy may deliver the same benefits as action observation because improved movement is observed and similar actions are performed (Buccino, 2014). Cortical motor areas activated when observing an action are similar to those activated while executing the comparable movement (Grèzes & Decety, 2001). Similar to this concept, the relationship between mirror visual feedback and motor imagery may also be of relevance (Stevens & Stoykov, 2003). Motor imagery can either be strengthened or hampered by looking in the mirror. Even when there is no action during observation, internal simulation of movement may occur, allowing neural circuits for motor control to be activated (Grèzes & Decety, 2001). There are several additional related hypotheses, but the mechanism for mirror therapy remains unknown.

Given that the ultimate goal of mirror therapy following stroke is to improve the motor function of the affected limbs of stroke patients, observing the movements of the unseen affected hand during mirror therapy should provide a more comprehensive understanding. If studies show that affected limb movement is enhanced during therapy sessions, the case for mirror therapy may be strengthened. To the best of my knowledge, no studies have examined hand movement behind the mirror in clinical populations, and analysis of movements that occur during interventions rather than after mirror therapy has never been explored.

Bimanual coordination in mirror visual feedback

Unseen hand movements can be better understood through motor control investigations of bilateral movements performed by unimpaired participants under mirror visual feedback. As in general bilateral training, interlimb coupling between the arms can be expected in bimanual execution with mirror visual feedback. Simultaneous movement of the unaffected limb may enhance the movement of the affected limb (Cauraugh et al., 2010; McCombe Waller et al., 2008), and the additional use of a mirror is postulated to further aid the improvement of motor function by giving "proper" feedback (Altschuler, 2005).

Franz and Packman (2004) demonstrated how the mirror reflection of the seen hand directly affects the motor output of the unseen hand in unimpaired participants. They recruited 15 unimpaired volunteers and asked them to draw circles with both hands at their own pace. The task was completed under four different conditions: left hand vision with and without mirror, left hand vision with and without mirror. Eight trials were conducted for each condition, and each trial lasted 8 seconds. During trials, participants were asked to gaze at the boundary between the table and the mirror. Researchers examined the sizes of circles drawn by both hands and also analysed the phase difference between the hands to assess spatial and temporal coupling. The result for circle size demonstrated the influence of the mirror. When there was no mirror, participants drew smaller circles with the unseen hand than with the seen hand. However, when a mirror was present, the circle size of both hands became more comparable. This finding shows that mirrors can enhance the spatial coupling of both hands.

Through bimanual circle drawing, Metral et al. (2014) also demonstrated the difference in bimanual performance when a mirror was present or absent. They revealed the difference in bimanual coordination by applying sensorimotor disturbances (vibrators) to the unseen hand. The circular size of the unseen hand was reduced under all conditions when the sensory disturbance was introduced to it. However, the difference in circle size between hands was higher when there was an opaque screen than when there was a mirror. As with Franz and Packman (2004), this finding indicates that the presence of a mirror enhances bilateral coordination compared to when it is veiled.

However, these two motor control investigations both utilised methods that deviated from those typically used in mirror therapy protocols with patients. To begin with, the gaze point was different. In clinical studies, patients are advised to gaze straight at the mirror image (i.e. the illusory hand), whereas in the motor control studies outlined above, participants were instructed to focus on the boundary between the mirror and the table. Since the illusion generated by the mirror is considered critical to mirror therapy, the gaze point may be an important factor. The second difference would be the length of the trial. In motor control experiments, the trial finished with roughly 5 or 8 movements; however, in actual mirror therapy, more repeated movements are typically required continuously and for a longer duration. Intensity or duration is a critical aspect in constructing an intervention; therefore, it appears to be one of the factors to be examined and developed (Michielsen et al., 2011; Yavuzer et al., 2008).

Nonetheless, research on bimanual coordination with mirror visual feedback has revealed that the mirror encourages spatial coupling of both hands more than when only one hand is visible. With relation to using mirror therapy for motor rehabilitation, this potential to alter the unseen hand's motor output is very promising and has not been thoroughly studied before. In this thesis, the intention was to investigate the unseen hand movements based on bimanual coordination in the same manner as actual mirror therapy.

In the first experimental chapter (Chapter 2), the experiment largely replicates Franz and Packman's (2004) experiment. Movement of both hands were explored during continuous bimanual circle drawing with and without a mirror. The expectation was that positional drift of the unseen hand would occur during the mirror condition. Positional drift is a kinematic term introduced in this study based on previous references to proprioceptive drift, which is the biased action of the unseen hand toward the position of the illusory hand (Tajima et al., 2015). Positional drift describes the difference in unseen hand position at the start and the end of a trial. As the drift is explained by participants' adapting their movements in response to illusory visual feedback, the term 'proprioceptive drift' appeared misleading and so the term 'positional drift' was used. A second experiment in Chapter 2 investigated the impact of visual template on motor control.

The movement of the unseen hand was monitored on a movement-by-movement basis in the second experimental chapter (Chapter 3) using a repetitive aiming task. Chapter 3 attempted to see the relationship between the seen and unseen hands and, by carefully measuring the relations between the seen and unseen hands, attempted to examine the veracity of the mirror illusion throughout the trial, asking *Do participants move the unseen limb in a manner consistent with embodying the illusory limb?*.

It is thought that a critical factor of mirror therapy is how much the participants embody the illusory limb (McCabe, 2011). Sense of embodiment encompasses three subcomponents. This includes whether the mirror image appears to be your own (ownership), whether you feel that the limb in the mirror is under your control (agency), and whether you feel that the mirror image represents the location of the unseen hand (location) (Longo et al., 2008). Given the three characteristics above, if the participant embodies a mirror image, movements of the unseen hand during mirror visual feedback will be followed by illusory information with consistent impact. So far, most embodiment studies (including ownership and agency studies) have used Likert scales to assess participants' perception in terms of agreement and disagreement (Longo et al., 2008; Moore, 2016). Chapter 3 attempted to analyse whether adjustments of the unseen limb were consistent with illusory information as a means of providing a more objective measure of embodiment of the illusory limb.

In the following chapter (Chapter 4), the same method as Chapter 3 was applied to a small number of stroke patients with left hemiparesis. The same analysis procedure was used, and the results were interpreted in light of data collected from unimpaired participants in Chapter 3.

Finally, in the final experimental chapter (Chapter 5), (subjective) believability (embodiment) of the illusion was studied in unimpaired participants examining the impact of parameters known to modify the effectiveness of the mirror therapy (Morkisch et al., 2019). Embodiment can be simply investigated as a sense of realism (Rowe, 2019) or a peculiarity (Fink et al., 1999) in the mirror image during mirror visual feedback. Beyond simply feeling that the image in the mirror is yours (ownership), the participant's believability more naturally judges the embodiment of believing that the hand is your own. In other words, this is a direct question of self-identification, not just in terms of how participants recognise the movement of the illusory limb (Gallagher, 2000), but also in terms of how they can distinguish between self-generated action and movement on the exterior world (Jeannerod, 2006). Therefore, the degree of embodiment in the illusory limb was explored in Chapter 5 by investigating believability in various mirror therapy settings.

Chapter 2: *Through the Looking-Glass*: Mirror feedback modulates temporal and spatial aspects of bimanual coordination

The current chapter was presented at the 'UK Sensorimotor 2019' and 'Society for Neuroscience 2019' conferences.

Abstract

Mirror therapy has become an effective and recommended intervention for a range of conditions affecting the upper limb (e.g. hemiparesis following stroke). However, little is known about how mirror feedback affects the control of bimanual movements (as performed during mirror therapy). In preparation for future clinical investigations, this chapter examined the kinematics of bimanual circle drawing in unimpaired participants both with (Experiment 1) and without (Experiment 2) a visual template to guide movement. In both experiments, 15 unimpaired right-handed participants performed self-paced continuous bimanual circle-drawing movements with a mirror/symmetrical coordination pattern. For the *mirror* condition, the vision was directed towards the mirror in order to monitor the reflected limb. In the *no mirror* condition, the direction of vision was unchanged, but the mirror was replaced with an opaque screen. The movements of both hands were recorded using motion capture apparatus.

In both experiments, the most striking feature of movements was that the hand *behind the mirror* drifted spatially during the course of individual trials. Participants appeared to be largely unaware of this marked positional change of their *unseen* hand, which was most pronounced when a template to guide movement was visible (Experiment 1). Temporal asynchrony between the limbs was also affected by mirror feedback in both experiments; in

the *mirror* condition, the illusory vision of the *unseen* hand led to a relative phase lead for that limb. The data highlight the remarkable impact that the introduction of a simple mirror can have on bimanual coordination. Modulation of spatial and temporal features is consistent with the mirror inducing a rapid and powerful visual illusion; visual capture of movement in the *unseen* hand appears to override proprioceptive signals. The strength of this illusion can be augmented by including a visual template to guide movement, and this may have utility in rehabilitation.

Introduction

Mirror visual feedback of movement provides the basis for mirror therapy, an intervention that has become increasingly prevalent over the past 20 years in the management of various conditions such as chronic pain and stroke. In the case of stroke, mirror therapy has primarily been used to target resulting hemiparesis of the upper limb; a recent systematic review reported its ability to improve both motor function and motor impairment in this group of patients (Thieme et al., 2018).

Before considering how mirror therapy might work, this chapter first describe the approach. The typical arrangement during mirror therapy is as follows. The patient sits with their arms resting on a table with a mirror aligned to their mid-sagittal plane, the reflective side facing towards the unimpaired limb. The patient is then encouraged to make congruent and synchronous bimanual movements while focusing their visual attention on the reflection of the unimpaired limb in the mirror. The resulting illusion can be rapidly elicited and vivid. As the reflection of the *seen* hand in front of the mirror appears spatially congruent with the felt position of the *unseen* hand behind the mirror, one's experience is of actually viewing the unseen hand. The experience appears strengthened by movement, providing the intended movement and the visual consequences remain congruent.

As referred to above, while mirror therapy training has been found to have significant benefits, understanding how mirror therapy works has proved elusive. At the neural level, there appear to be multiple possibilities. Deconinck *et al.* (2015) explored three related hypotheses in providing a meta-analysis of published data. Finding little support for the involvement of the *mirror neuron system*, the authors suggest mirror therapy activates a network of brain areas relating to monitoring action and attention. An alternative possibility is that mirror therapy is associated with the activation of the normally inhibited ipsilateral (contra-lesional) motor pathways, thought to play a role more generally in the recovery (Schwerin et al., 2008).

At the behavioural level, complexities of the intervention are challenging for researchers as the therapeutic benefits may arise from a number of different sources. For example, research suggests that bimanual movement training (in the absence of a mirror) may also have clinical benefits (Cauraugh et al., 2010), providing the real possibility that it is simply the performance of these movements alone that conveys therapeutic value. Nevertheless, one suggestion that appears worthy of consideration is that mirror visual feedback facilitates the bimanual coupling (Guerraz, 2015). This issue has not been examined in stroke survivors to date, though two studies have addressed the impact of a mirror on bimanual coordination in unimpaired individuals (Franz & Packman, 2004; Metral et al., 2014). Both these studies used a bimanual circle-drawing task and focused on how mirror visual feedback modulated spatial and temporal aspects of bimanual coordination. The most striking feature across both studies was a tendency for more equal circle size (i.e. greater spatial coupling) when the mirror was present in comparison to when it was replaced by an opaque screen. Neither study found a modulatory effect of mirror visual feedback on the small asynchronies that are typically found for the task.

A surprising aspect of these studies was that neither examined any changes that occurred in limb position during trials. Previous studies examining reaching movements with mirror visual feedback highlight that conflict between proprioceptive and visual signals about the position of the unseen limb can lead to significant errors (Holmes & Spence, 2005; Holmes et al., 2004), with vision dominating perception, particularly in relation to position along the sagittal plane (Snijders et al., 2007). Consistent with these findings, the author's informal observations of limb position when making bimanual circle-drawing movements with mirror visual feedback suggested a tendency for the unseen hand to *drift*, particularly along the sagittal plane. These observations together with previous findings, were the motivation for this study of unimpaired participants in preparation for future clinical studies.

This study largely aimed to replicate the experiment conducted by Franz and Packman (2004) but with some differences. Firstly, the trial length was increased from eight seconds to 15 seconds; some have argued that the onset of the mirror illusion follows around six seconds of exposure, and this study aimed to provide sufficient time to observe the effects of the illusion. Secondly, a visual template was introduced to provide participants with explicit spatial information about the position and size of the circles to be drawn. Thirdly, while including the same conditions as Franz and Packman (2004), instructions to participants about where to direct their vision were modified. Rather than have participants direct their visual attention to the junction between the table and the mirror, they were encouraged to direct their visual attention to their hand reflected in the mirror. This was done to provide a more authentic representation of how mirror therapy typically proceeds (Ramachandran & Altschuler, 2009; Rothgangel et al., 2011).

The primary hypothesis related to *proprioceptive drift*. In contrast to studies reported by Franz and Packman (2004) and Metral et al. (2014), the position of the centre of circles was tracked as trials unfolded. Given our informal observations noted above, along with studies reporting conflicts between vision and proprioception in different tasks using mirror visual feedback (Holmes & Spence, 2005; Holmes et al., 2004; Snijders et al., 2007; Tajima et al., 2015), it was hypothesised that the unseen hand would show positional drift in the *mirror* conditions, driven by the incongruence of peripheral sensory information. In addition, circle size and between-limb synchrony were also monitored, consistent with the studies of Franz and Packman (2004) and Metral et al. (2014).

Experiment 1 Methods

Participants

The participants were 15 (4 female) volunteers (mean age: 26.3 $\pm$ 7.5 years) drawn from the staff and student body at the University of Birmingham. All self-reported being right-handed, and this was confirmed with the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971); mean score = 98.7 $\pm$ 4.99. All participants were unimpaired and were naïve to the purpose of the study. The study was approved by the University of Birmingham's Science, Technology, Engineering and Mathematics Ethical Review Committee. Participants provided written informed consent prior to taking part.

Apparatus

The experiment was conducted in the Motor Cognition Laboratory within the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. The room was kept silent to help participants' concentration, and the workspace was free from any unnecessary objects.

Limb movements were recorded by a 3-camera motion capture system (ProReflex, Qualisys Ltd., Sweden) sampling at a rate of 200 Hz. Small, reflective spherical markers tracked by the cameras were placed on the index fingernail of each hand using double-sided sticky tape.

A mirror (50 cm x 40 cm) was placed (short side down) on the table, its edge flush with the table edge and aligned to the participant's mid-sagittal plane (see Figure 2.1). The mirror was held in place by two small bespoke wooden mounts. The participant's hands initially rested on the table at either side of the mirror and at an equal distance from it. A template, printed on an A0 piece of paper and fixed to the table. At either side of the mirror and an equal distance from it, an 8.5 cm diameter circle was printed and formed a visual template to guide the participants' circle-drawing movements. The distance between the circle centres was 35.8 cm. A small cross at the *top* ('12 o'clock') of each circle (30 cm from the table edge) indicated the starting position for the participant's index fingertips on all trials.

Task, design and procedure

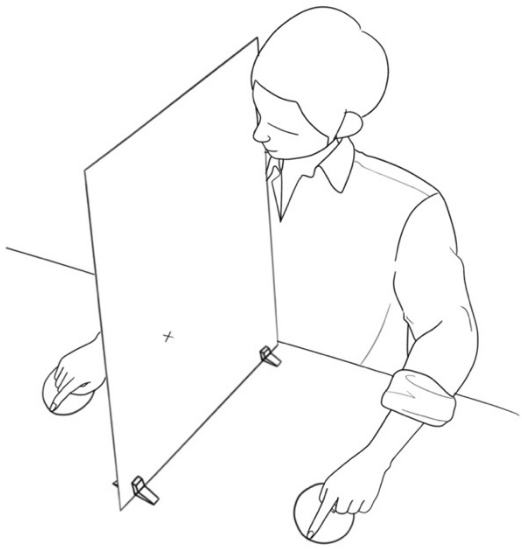
Trials required participants to draw continuous self-paced circles with both hands for 15 seconds. Although the pace of circle drawing was not formally constrained, participants were asked to move at an approximate rate of one circle per second. Circles were drawn with pointing index fingers, keeping the fingertips in contact with the template surface at all times. Upper limb movements were largely restricted to involving motion at the shoulder and elbow joints, but wrist and finger movements were not physically restricted. The index fingertips were the only points of contact between the participant and the table. Starting at the starting position on the templates, movements proceeded in a synchronised mirror-symmetrical manner, with the right hand moving in a clockwise (CW) direction and the left hand in a counterclockwise (CCW) direction. Given the trial length (15 s) and movement speed, participants completed approximately 15 circles with each hand on every trial.

Participants performed 40 trials during Experiment 1, and there were four conditions; participants completed ten trials per condition. The four conditions (see Figure 2.1) were as follows; left hand visible without mirror (Left Vision), left hand visible with mirror (Left Mirror), right hand visible without mirror (Right Vision) and right hand visible with mirror (Right Mirror). Conditions were randomised across trials. For *Mirror* conditions, the reflective surface of the mirror was on the same side as the participant's head and the participant was instructed to direct their vision to the reflection of their hand in the mirror. For *No mirror* conditions, the mirror was positioned the opposite way around so that the opaque surface was at the same side as the participant's head. For these trials, the participant was instructed to direct their vision toward a fixation cross that was placed on the opaque surface of the mirror spatially consistent with the position of the reflected hand in the *Mirror* conditions.

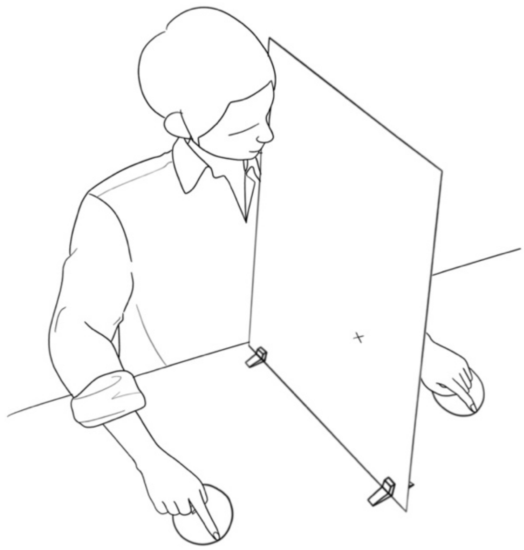
Prior to the experiment, participants completed the EHI and were given written instructions about the procedure to read. Any subsequent questions were answered. Participants then proceeded to complete a small number of practice trials before the experimental trials began. Where necessary, a metronome was used during practice trials to indicate the approximate speed of movements. Trials began with a verbal 'go' signal from the researcher and ended with a verbal 'stop' signal. A short rest was given between trials, and 5 minutes of scheduled break was given after 20 trials.

Data analysis

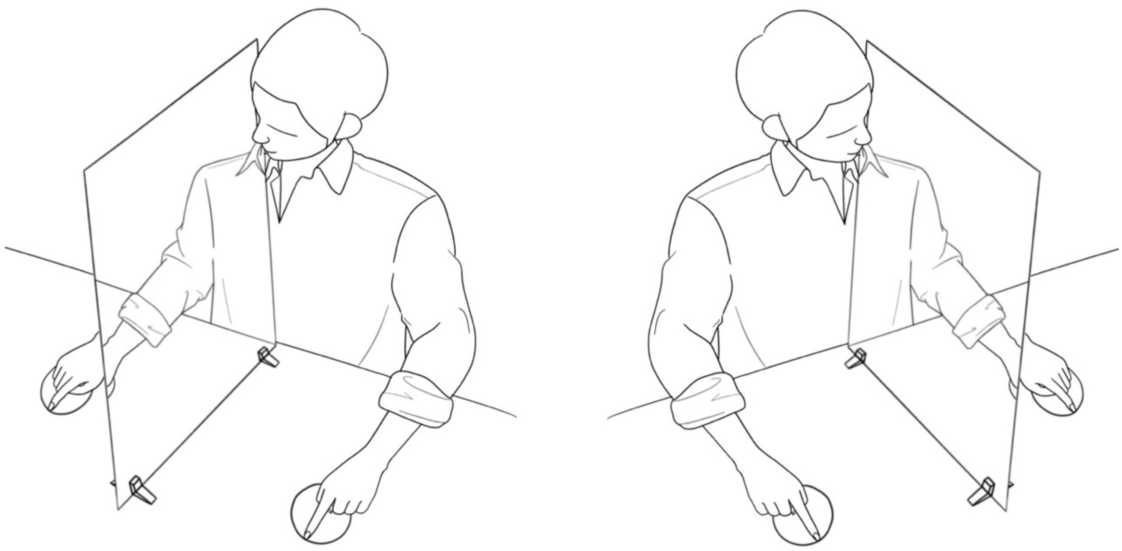
Kinematic data were exported and analysed offline using bespoke software (Matlab 2019b, Mathworks Inc., Natick, MA, USA). Signals were rectified and filtered with a 4th-order low-pass Butterworth filter using a cut-off of 20 Hz. The main variables of interest were circle circumference, positional drift, and inter-limb asynchrony. Positional drift was the primary outcome, with circle circumference and inter-limb asynchrony as secondary outcomes. The analysis proceeded by separating the continuous circles into individual circles. The first cycle of each circle started from the minimum value for the x-axis in the left hand (i.e. the furthest point leftwards) and the maximum value for the x-axis in the right hand (i.e. the furthest point rightwards). The same subsequent points for each circle represented the end of the completed circle and the start of the new circle.



2.1-a Left Vision



2.1-c Right Vision



2.1-b Left Mirror 2.1-d Right Mirror

Figure 2.1 Experimental conditions. Four conditions were made by crossing the Head side (Left, Right) and Mirror (Mirror, Vision) variables. The Head side presents where the head is placed relative to the mirror, and the Mirror shows whether facing the mirror or the opaque screen. When the mirror was present, participants looked at the tip of the index finger in the mirror. When the mirror was removed, the vision was fixed at the 'x' mark.

Dependent variables were defined accordingly:

Positional drift - calculated for each trial and represented by a straight line between the centre of the circle farthest from the centre of the first drawn circle. The centre of the circle was determined by taking the values halfway between the maximum and minimum values in the x and y-axis.

Circumference - the trajectory length of each circle.

Inter-limb asynchrony - calculated at the end of every individual circle by comparing the frame number at which each limb reached this point. In each cycle, the frame number of the right limb was subtracted from that of the left limb. Thus, a negative value referred to a left limb lead (right limb lag) and positive values referred to a right limb lead (left limb lag). Since movement was captured at 200 frames/sec, a difference of one frame represents 5 msec (0.005 sec).

Statistical analysis

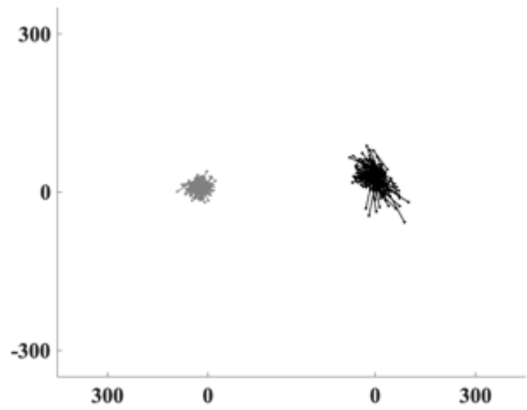
Data were analysed by using SPSS (IBM SPSS Statistics, Version 25.0. Armonk, NY, USA) and all normality checks were conducted. The data were normally distributed and appropriate for analysis using parametric tests. Individual mean values were calculated for the factors of interest. *Positional drift* and *Circumference* data were analysed via a 2 × 2 × 2 (*Head side* [left, right] × *Mirror* [mirror, opaque screen] × *Hand* [seen, unseen]) analysis of variance (ANOVA) with repeated measures. *Inter-limb asynchrony* data were analysed via a 2 x 2 (*Head side* [left, right] x *Mirror* [mirror, opaque screen]) ANOVA with repeated measures. The interactions between simple effects were analysed with multiple comparison subject to Bonferroni correction. The threshold for statistical significance was set to $p < 0.05$.

Experiment 1 Results

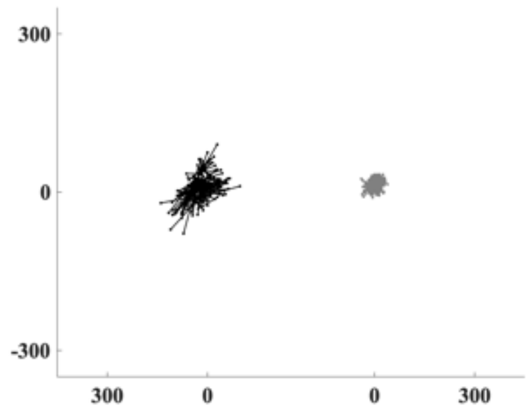
Positional drift

Figure 2.2 shows drift lines that represent the extent of positional drift for every trial; for both hands and for each condition. Figure 2.3 shows the related group mean values. There were significant main effects of *Mirror*, $F(1,14) = 72.86$, $p < 0.001$, $\eta_p^2 = 0.839$ and *Hand*, $F(1,14) = 174.21$, $p < 0.001$, $\eta_p^2 = 0.926$ and also a *Mirror* x *Hand* interaction, $F(1,14) = 88.92$,

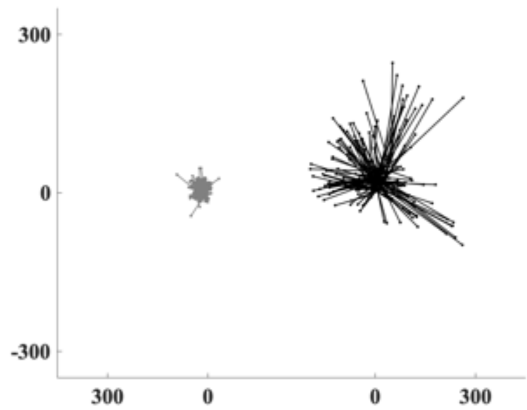
$p < 0.001$, $\eta_p^2 = 0.864$. As can be seen in Figure 2.3, the interaction is explained by the impact of the *mirror* on the *unseen* hand. Accordingly, the positional drift of the *seen* hand was comparable regardless of whether the mirror was in place or not, $F(1,14) = 0.01$, $p = 0.926$, $\eta_p^2 = 0.001$. However, the positional drift of the *unseen* hand was significantly greater when the mirror was in place, $F(1,14) = 82.13$, $p < 0.001$, $\eta_p^2 = 0.854$.



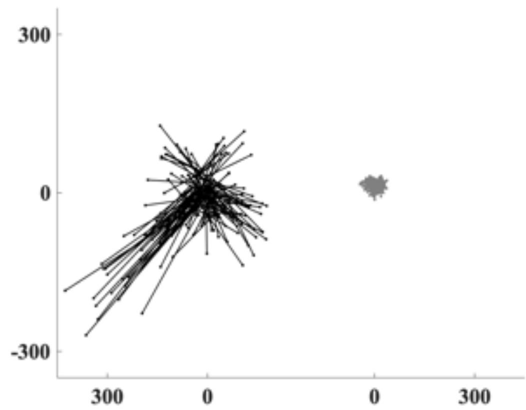
2.2-a Left Vision



2.2-c Right Vision



2.2-b Left Mirror



2.2-d Right Mirror

Figure 2.2 Positional drift in Experiment 1. Lines represent positional drift on every trial as a function of the Head side, Mirror and Hand. The ends of each line reflect the centre of the first circle to the centre of the furthest circle drawn. Scale values are in millimetres.

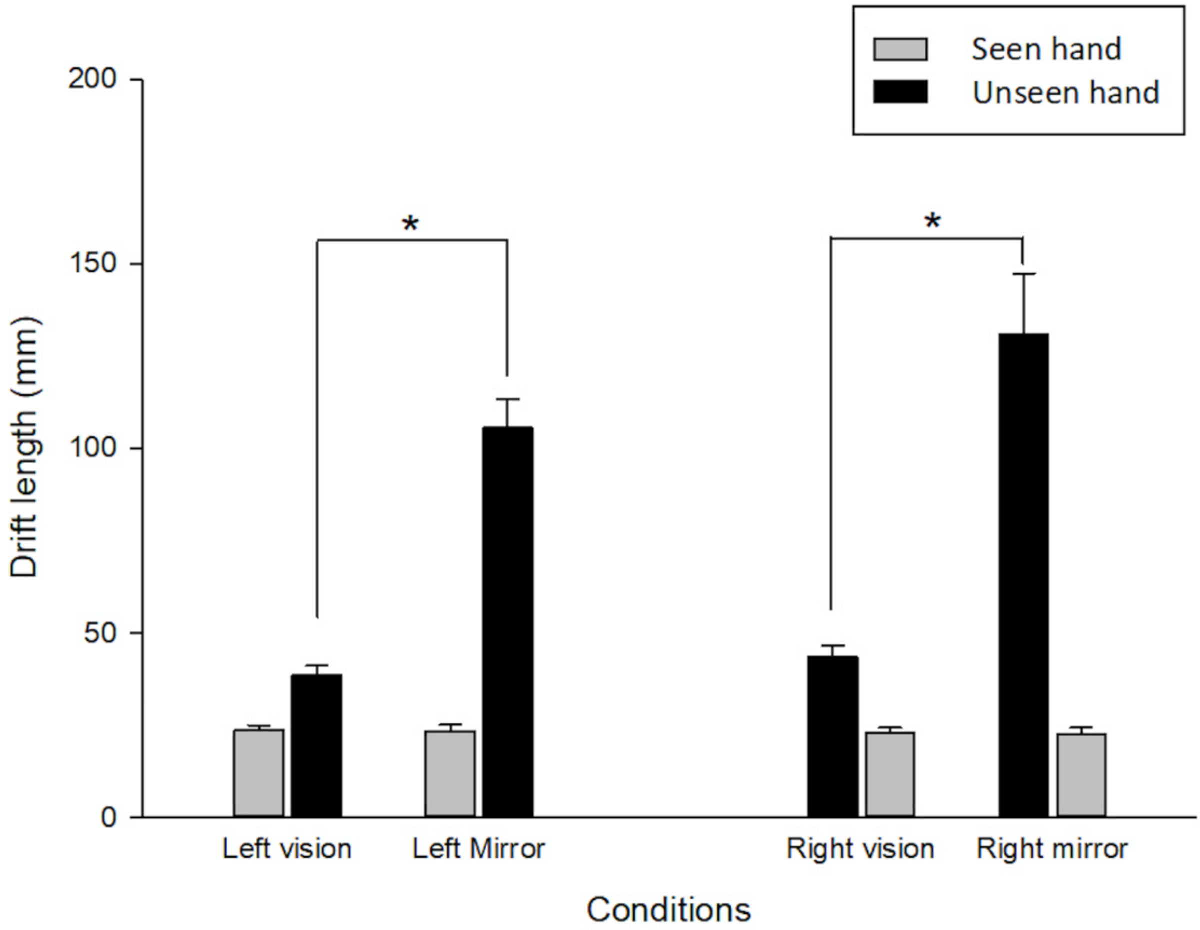


Figure 2.3 Mean drifts for the four conditions in Experiment 1. Error bars denote standard error, and asterisks denote statistical significance. Seen hand and unseen hand depend on the Head side. In the case of the left head side, the seen hand becomes the left hand, and the unseen hand becomes the right hand. In the case of the right head side, the seen hand is changed to the right hand and the unseen hand to the left hand.

Circumference

Across the experiment, mean circumference was larger when the mirror was in place (mean = 266.15 $\pm$ 38.71mm) than when replaced by an opaque screen (mean = 255.75 $\pm$ 45.34mm), leading to a significant main effect of *Mirror*, $F(1,14) = 5.03$, $p = 0.042$, $\eta_p^2 = 0.264$. Additionally, the *seen* hand (mean = 267.35 $\pm$ 39.57mm) made circular movements that had a significantly larger circumference than the *unseen* hand (mean = 254.55 $\pm$ 44.28mm), $F(1,14) = 13.90$, $p = 0.002$, $\eta_p^2 = 0.498$. However, *Head Side* x *Hand*, $F(1,14) = 8.69$, $p = 0.011$, $\eta_p^2 = 0.383$, *Mirror* x *Hand*, $F(1,14) = 13.85$, $p = 0.002$, $\eta_p^2 = 0.497$ and *Head Side* x *Mirror* x *Hand*, $F(1,14) = 8.68$, $p = 0.011$, $\eta_p^2 = 0.383$ interactions suggested a more complex relationship between factors. The results of the complex interaction are shown in Figure 2.4. When the head was to the *left*, there was no *Mirror* x *Hand* interaction, $F(1,14) = 0.96$, $p = 0.344$, $\eta_p^2 = 0.064$, with the *seen* (left) hand consistently drawing larger circles. However, when the head was placed to the *right*, there was a *Mirror* x *Hand* interaction, $F(1,14) = 22.66$, $p < 0.001$, $\eta_p^2 = 0.618$. Here, the *seen* (right) hand only drew smaller circles in the *no mirror* condition, $F(1,14) = 7.70$, $p = 0.015$, $\eta_p^2 = 0.355$. In the mirror condition, circumferences were comparable, $F(1,14) = 0.10$, $p = 0.753$, $\eta_p^2 = 0.007$.

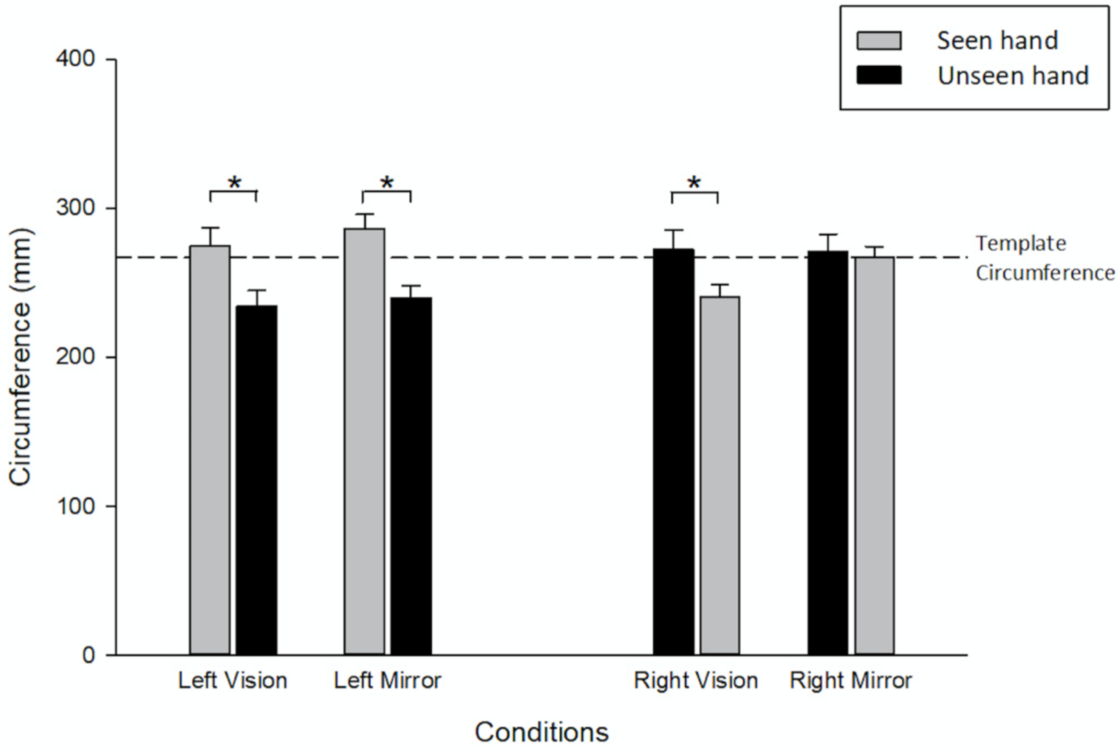


Figure 2.4 Mean circumferences for the four conditions in Experiment 1. Error bars denote standard error, and asterisks denote statistical significance. Seen hand and unseen hand depend on the Head side. In the case of the left head side, the seen hand becomes the left hand, and the unseen hand becomes the right hand. In the case of the right head side, the seen hand is changed to the right hand and the unseen hand to the left hand.

Inter-limb asynchrony

Across the experiment, there was a small right (dominant) hand lead (mean = 39.38 $\pm$ 47.38ms). When the head was positioned to the left (i.e. looking in a rightwards direction), the right-hand lead was increased (mean = 59.59 $\pm$ 47.30ms). The right-hand lead was reduced when the head was positioned to the right (i.e. looking in a leftwards direction) (mean = 19.17 $\pm$ 38.55ms). There was a related significant main effect of *Head Side*, $F(1,14) = 22.83$, $p < 0.001$, $\eta_p^2 = 0.620$. However, as can be seen in Figure 2.5, these differences were modulated further by the presence of the mirror. Indeed, the presence of the mirror (and subsequent vision of an illusory hand) appeared to accentuate the changes in asynchrony as a result of *Head Side*. There was a resulting *Head Side* x *Mirror* interaction, $F(1,14) = 6.80$, $p = 0.021$, $\eta_p^2 = 0.327$. However, exploring the simple effects of this interaction only revealed a *Mirror* effect when the head was positioned to the left, $F(1,14) = 7.05$, $p = 0.019$, $\eta_p^2 = 0.335$. The corresponding effect when the head was positioned to the right was not statistically reliable, $F(1,14) = 3.98$, $p = 0.066$, $\eta_p^2 = 0.221$.

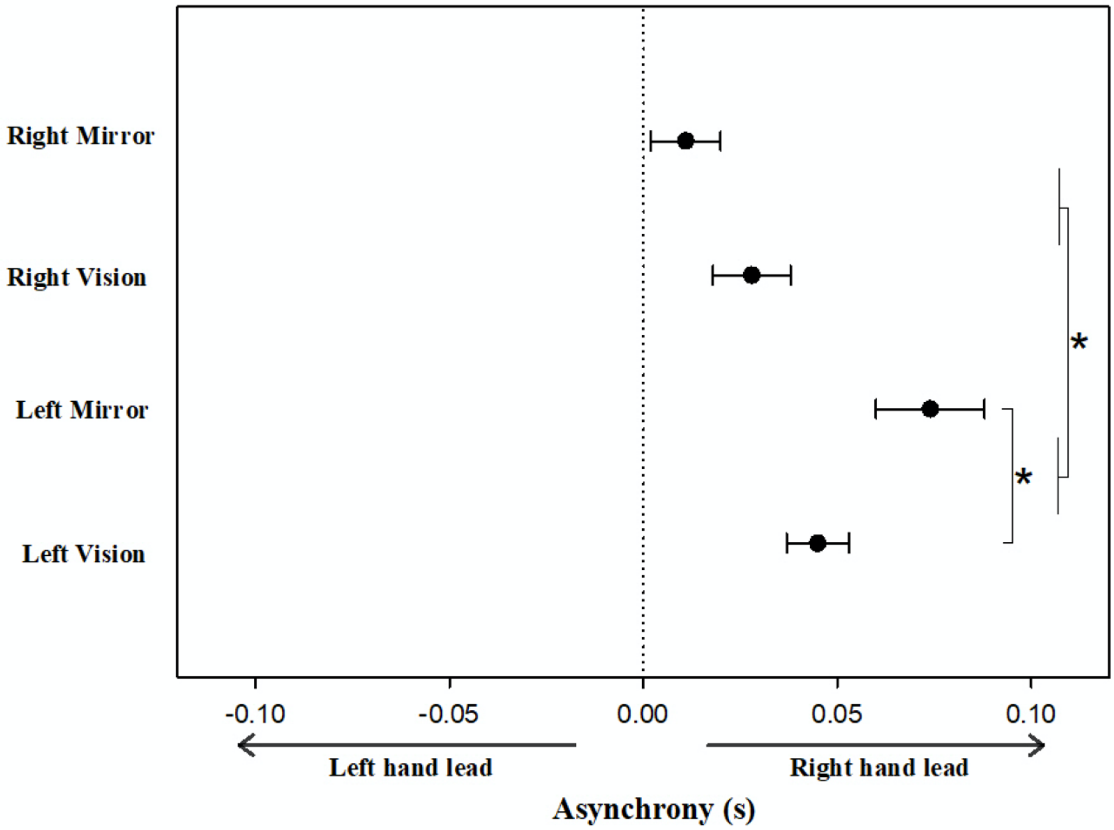


Figure 2.5 Mean inter-limb asynchronies for the four conditions in Experiment 1. Error bars denote standard error, and asterisks denote statistical significance. Seen hand and unseen hand depend on the Head side. In the case of the left head side, the seen hand becomes the left hand, and the unseen hand becomes the right hand. In the case of the right head side, the seen hand is changed to the right hand and the unseen hand to the left hand.

	Circumference (mm)		Positional drift (mm)		Inter-limb asynchrony (sec)
	Left hand	Right hand	Left hand	Right hand	
Left Vision	275.19 (11.98)	234.45 (10.29)	32.12 (1.55)	43.67 (2.44)	0.05 (0.03)
Left Mirror	286.45 (9.46)	239.79 (8.12)	34.84 (2.63)	114.78 (7.21)	0.07 (0.06)
Right Vision	272.88 (12.52)	240.48 (8.63)	50.52 (2.92)	28.22 (1.35)	0.03 (0.04)
Right Mirror	271.11 (11.60)	267.26 (7.08)	142.87 (15.98)	31.79 (2.20)	0.01 (0.04)

Table 2.1 Mean (and standard error) values of dependent variables in Experiment 1.

Experiment 1 Discussion

In this study, the kinematics of bimanual circle-drawing movements in unimpaired participants with and without mirror visual feedback were examined. Participants completed a series of 15-second trials (drawing approx. one circle per second) under four different conditions.

Circle circumference and inter-limb asynchrony were both significantly modulated by the mirror and showed some similarities with findings from previous studies. These findings will be discussed in more detail in the *General Discussion* (see later). However, the most striking feature of the experiment was the very marked positional drift of the unseen hand during mirror visual feedback conditions. While some drift of the unseen hand was also observed during no mirror conditions (i.e. when the vision of the limb was simply occluded), the marked increase in the drift when the mirror was present was remarkable. Indeed, at the end of such trials, participants appeared very surprised by the new position of the limb behind the mirror. At times during the experiment, participants reacted at the end of *mirror* trials with comments such as “I feel stupid”, “That’s weird”, and “This cannot be” in response to finding their unseen hand in a position some distance from where they had expected it to be.

The positional drift observed for the unseen hand displayed some consistency with previous studies showing positional errors on reaching tasks but extends these findings to highlight the effects and implications of mirror visual feedback for a continuous task. For instance, under similar mirror conditions, Holmes and colleagues reported how observation of a static hand positioned so there is a small offset between the perceived visual and proprioceptive (felt) positions of the unseen hand, is sufficient to elicit a reaching error (Holmes et al., 2004). However, note this was not the case when the seen and felt positions of the unseen hand were congruent. Subsequent work demonstrated how these errors were enhanced if preceded by a few seconds of active movement (Holmes & Spence, 2005).

In the present study, the starting position was designed so that the perceived seen and felt positions of the unseen hand were congruent. Nevertheless, it appears that small corrective movements of the unseen hand in response to small deviations away from the template with the seen hand were sufficient to elicit substantial positional drift across the length of a trial. The continuous task provided the conditions for these small *corrective* movements of the unseen hand to contribute incrementally to the considerable positional drift observed in some trials. Indeed, it seems likely that the relatively slow development of positional drift across successively drawn circles was the reason why such large discrepancies between the seen and felt positions of the unseen hand remained unchecked.

The length of trials in Experiment One may also have been a contributing factor, allowing time for the drift to take place (Paillard & Brouchon, 1968). The 15 s selected for trials was considerably longer than those reported by Franz and Packman (2004) and Metral et al. (2014), with neither of these previous studies reporting positional drift. However, perhaps an even more pertinent difference from these previous studies that could account for the considerable drift observed was the use of a visual template. By providing such clear and unambiguous guidance for movements, participants effectively attempt to *trace* their fingers around the template circles. In doing so, if the seen hand deviated away from the template (even fractionally), providing the mirror illusion was operating, the participant would make small corrective movements of their unseen hand in an attempt to correct hand position in line with the visual information they received. This may be the mechanism that accounts for the substantial drift observed. In a task where visual and proprioceptive feedback contribute to control, it seems likely that providing such explicit visual guidance enhances attention towards visual signals with less attention paid to proprioceptive signals. In Experiment Two, this hypothesis was empirically tested by replicating the study in the absence of a visual template.

Experiment 2 Methods

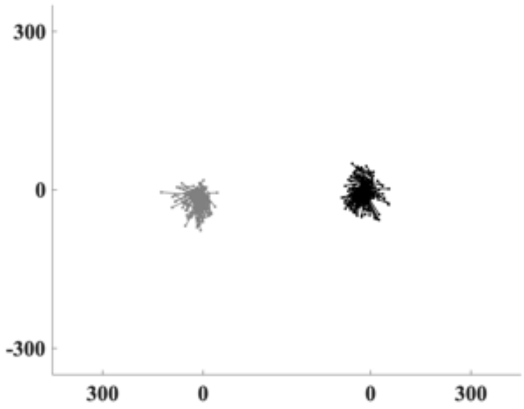
Fifteen right-handed (EHI mean score = 96.7 $\pm$ 8.69) participants (who had not participated in Exp. 1) took part in Exp. 2. They included five males and ten females (mean age: 21.6 $\pm$ 3.77) and were students at the University of Birmingham.

The procedure for Exp. 2 was identical to that of experiment 1, except for the template set-up. In this experiment, the template was removed. Therefore, at the start of each trial, the finger position was guided by the investigator so that the participant could start at the same position as the first experiment. Although the template was removed during the trial, participants spent a few minutes practising over the template (used for Exp. 1) to familiarise themselves with the approximate circle size required and the required hand position.

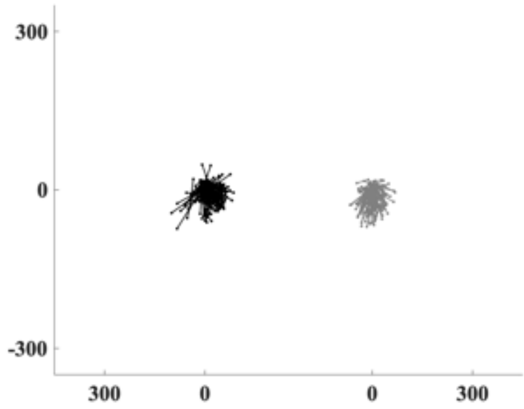
Experiment 2 Results

Positional drift

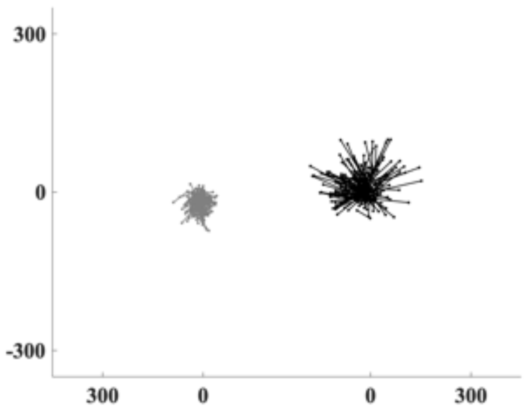
Figure 2.6 shows the extent of positional drift in each hand for every trial from each condition. There were significant main effects of *Mirror*, $F(1,14) = 57.57$, $p < 0.001$, $\eta_p^2 = 0.804$ and *Hand*, $F(1,14) = 82.68$, $p < 0.001$, $\eta_p^2 = 0.855$ and also a *Mirror* x *Hand* interaction, $F(1,14) = 52.35$, $p < 0.001$, $\eta_p^2 = 0.789$. As can be seen in Figure 2.7, the interaction is explained by the impact of the *mirror* on the *unseen* hand. Accordingly, the positional drift of the *seen* hand was comparable regardless of whether the mirror was in place or not, $F(1,14) = 0.29$, $p = 0.596$, $\eta_p^2 = 0.021$. However, the positional drift of the *unseen* hand was significantly greater when the mirror was in place, $F(1,14) = 67.48$, $p < 0.001$, $\eta_p^2 = 0.828$.



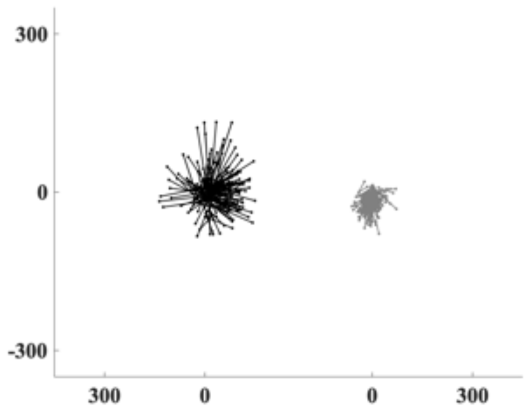
2.6-a Left Vision



2.6-c Right Vision



2.6-b Left Mirror



2.6-d Right Mirror

Figure 2.6 Positional drift in Experiment 2. Lines represent positional drift on every trial as a function of the Head side, Mirror and Hand. The ends of each line reflect the centre of the first circle to the centre of the furthest circle drawn. Scale values are in millimetres.

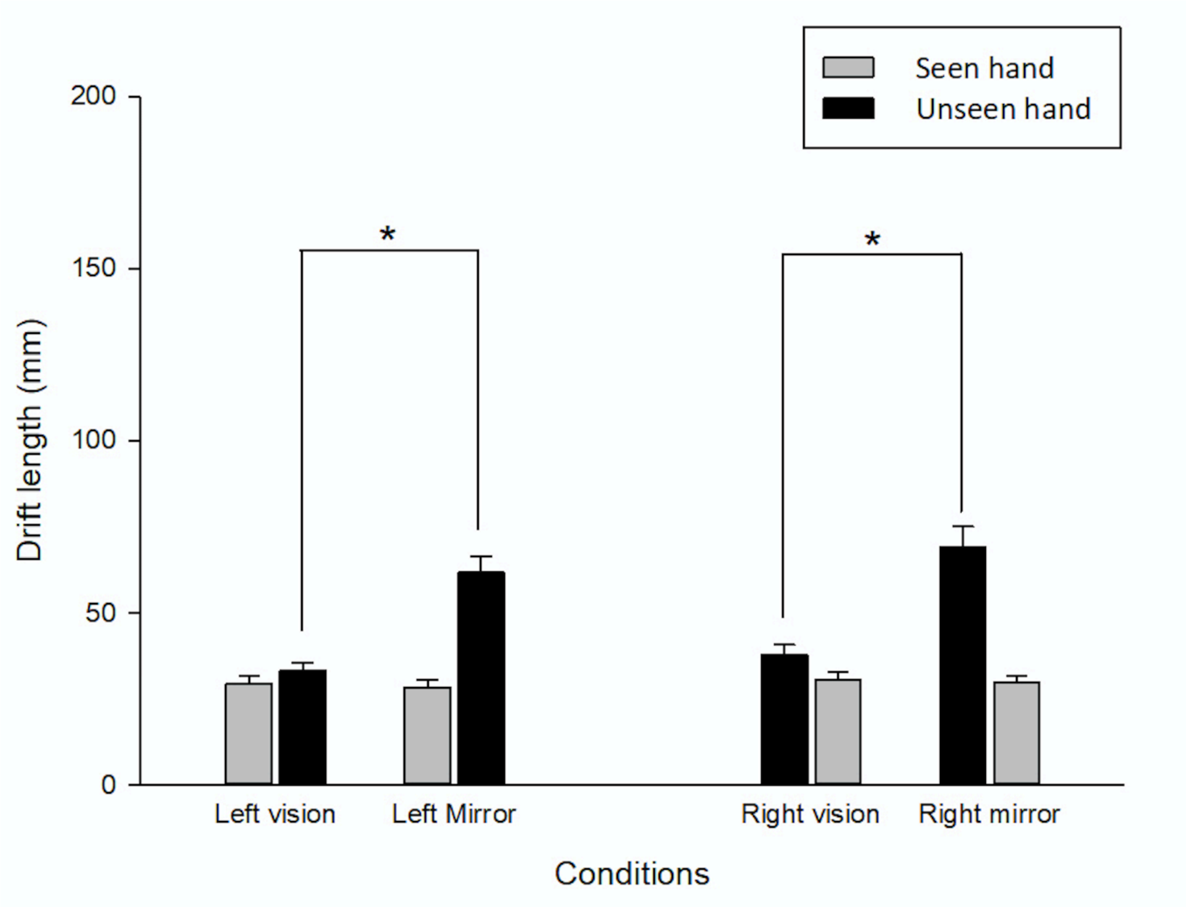


Figure 2.7 Mean drifts for the four conditions in Experiment 2. Error bars denote standard error, and asterisks denote statistical significance. Seen hand and unseen hand depend on the Head side. In the case of the left head side, the seen hand becomes the left hand, and the unseen hand becomes the right hand. In the case of the right head side, the seen hand is changed to the right hand and the unseen hand to the left hand.

Circumference

The ANOVA revealed a significant main effect of *Mirror*, $F(1,14) = 26.06$, $p < 0.001$, $\eta_p^2 = 0.651$; circumferences were larger when the mirror was in place (mean = 323.50 ± 47.25mm) than when replaced by an opaque screen (mean = 307.97 ± 41.48mm). There were no other significant main effects or interactions (see Figure 2.8).

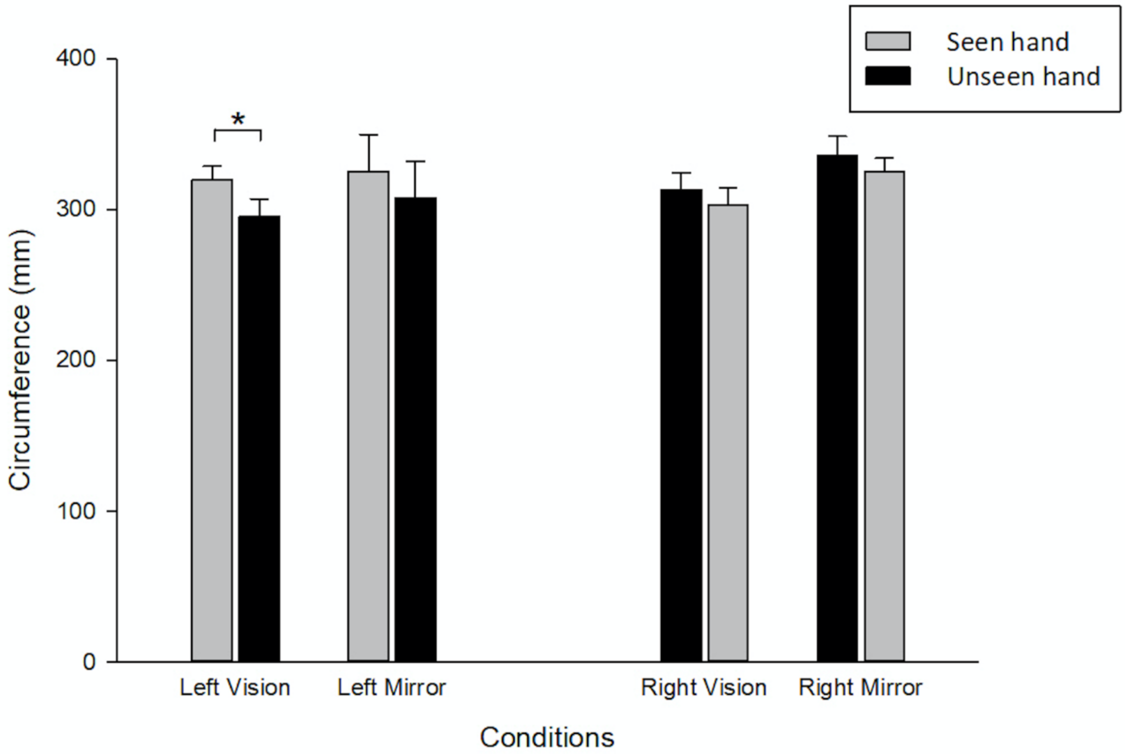


Figure 2.8 Mean circumferences for the four conditions in Experiment 2. Error bars denote standard error, and asterisks denote statistical significance. Seen hand and unseen hand depend on the Head side. In the case of the left head side, the seen hand becomes the left hand, and the unseen hand becomes the right hand. In the case of the right head side, the seen hand is changed to the right hand and the unseen hand to the left hand.

Inter-limb asynchrony

As with Experiment 1, there was a small right (dominant) hand lead across this experiment (mean = 16.91 $\pm$ 36.81ms). Similarly, when the head was positioned to the left (i.e. looking in a rightwards direction), the right-hand lead was increased (mean = 38.96 $\pm$ 31.68ms). This right-hand lead became a small left-hand lead when the head was positioned to the right (i.e. looking in a leftwards direction) (mean = -5.15 $\pm$ 27.33ms). There was a related significant main effect of *Head Side*, $F(1,14) = 35.41$, $p < 0.001$, $\eta_p^2 = 0.717$. However, as can be seen in Figure 2.9, these differences were again modulated by the presence of the mirror. The presence of the mirror (and subsequent vision of an illusory hand) accentuated the changes in asynchrony as a result of *Head Side*. Accordingly, there was a *Head Side* x *Mirror* interaction, $F(1,14) = 22.75$, $p < 0.001$, $\eta_p^2 = 0.619$. Exploring the simple effects of this interaction revealed a *Mirror* effect both when the head was positioned to the left, $F(1,14) = 17.03$, $p = 0.001$, $\eta_p^2 = 0.549$, and when the head was positioned to the right, $F(1,14) = 10.97$, $p = 0.005$, $\eta_p^2 = 0.439$.

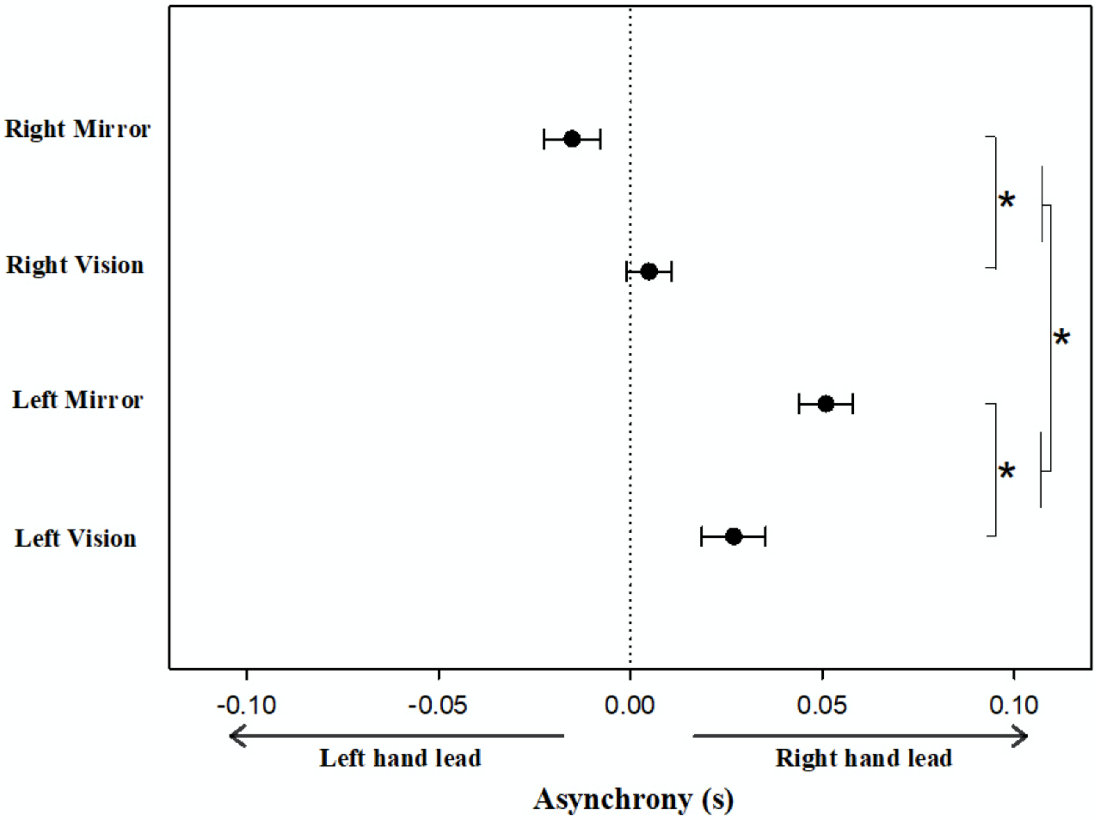


Figure 2.9 Mean inter-limb asynchronies for the four conditions in Experiment 2. Error bars denote standard error, and asterisks denote statistical significance. Seen hand and unseen hand depend on the Head side. In the case of the left head side, the seen hand becomes the left hand, and the unseen hand becomes the right hand. In the case of the right head side, the seen hand is changed to the right hand and the unseen hand to the left hand.

	Circumference (mm)		Positional drift (mm)		Inter-limb asynchrony (sec)
	Left hand	Right hand	Left hand	Right hand	
Left Vision	319.65 (9.05)	295.63 (11.53)	29.43 (8.69)	33.29 (8.33)	0.02 (0.01)
Left Mirror	325.30 (11.13)	307.56 (15.29)	28.44 (8.35)	61.70 (18.05)	0.05 (0.01)
Right Vision	313.37 (10.94)	303.22 (11.15)	37.94 (10.95)	30.72 (7.91)	0.01 (0.01)
Right Mirror	336.15 (12.41)	324.99 (9.25)	69.12 (23.18)	29.81 (7.18)	-0.02 (0.01)

Table 2.2 Mean (and standard error) values of dependent variables in Experiment 2.

Experiment 2 Discussion

In Experiment 1, it was contended that the marked positional drift observed for the unseen hand during mirror visual feedback trials was enhanced by the presence of a visual template. To investigate this account further, the visual template was removed in Experiment 2. Otherwise, the experiment was a direct replication of Experiment 1. Data from Experiment 2 support the above contention; positional drift was markedly reduced in the absence of a visual template (less than half that observed in Experiment 1). Nevertheless, the positional drift of the unseen hand was still evident and was enhanced in the mirror visual feedback condition. Removing explicit visual guidance (i.e. the visual template) did not therefore abolish the positional drift observed in Experiment 1, and we suspect that the visual information that remained available provides the basis for this. In the absence of a visual template, other visual information in the workspace offers a spatial reference for movement. For example, the edge of the table and the borders of the mirror, particularly the lower border as it meets the table, will have provided visual cues. Additionally, although the work surface was designed to be as clear and as clean as possible, small blemishes may have been present or emerged during the course of the experiment and provided further visual information. Such information provides an illusory vision of the unseen hand with visuo-spatial reference points leading to related corrective adjustments. These were far less marked in the absence of a visual template but appear to have remained influential. It is unclear whether the relative weighting of illusory vision and proprioception in controlling the position of the unseen hand was different across the two experiments. However, it is likely that more explicit and exacting visual guidance (i.e. by using a visual template as in Experiment 1) enhances the relative contribution of vision.

General Discussion

Overview

The experiments reported here both examined the kinematics of bimanual circle drawing movements executed with either a mirror or opaque screen placed in participants' mid-sagittal plane. Where this was a mirror, the setup was comparable with that used for mirror therapy in patient groups (e.g., hemiparetic stroke). As already noted, the marked positional drift of the unseen hand was a feature of both experiments, but different conditions also modulated spatial and temporal coupling. These findings are discussed in turn below before considering the wider implications of the work for theory and practice.

Positional drift

Although participants behaved as instructed by making reliable circular movements with both hands that were largely synchronised, the position of the unseen hand showed a very strong tendency to drift away from its starting position when the mirror was in place. This occurred whether the unseen hand was the dominant (right) hand or the non-dominant (left) hand.

Since positional drift was the primary outcome and has never been reported before, a post-hoc power analysis was conducted to determine whether the sample size of the experiment was sufficient. Remarkably significant results were found from the effect of the mirror on positional drift in the experiments, and post-hoc power analysis verified that a sample size of fifteen individuals was sufficient (shown 100% power from both experiments).

While the data analysis conducted here captures the maximum distance that the limbs moved away from the starting position within a trial, it is important to recognise that observation during trials suggested this was not due to large deviations for any single movement. Rather, the overall large deviations appeared to be caused by small but repeated (and consistent) deviations away from the starting position on consecutive movements. These small deviations appeared to cumulate, resulting in the overall large deviations observed.

The substantial positional drift of the unseen hand was a feature for the mirror condition of both experiments but was far more pronounced in Experiment 1 when there was a visual template guiding movement. Indeed, positional drift observed in the unseen hand was almost double when a visual template was present.

Perhaps the most satisfactory explanation of this lies in the impact of specific visual information on the recognition of 'error'. In the presence of a visual template guiding the circle-drawing movements, any deviation of the index finger away from this (however small) may be perceived as an error for the illusory limb. Providing the illusion is intact, participants then modify movements of their unseen limb in order to correct for the perceived error.

This of course, has no impact on the perceived error as this is generated by the seen limb. As movements of the seen limb are relatively consistent, the perceived error remains and subsequent corrective movements of the unseen limb continue, resulting in the large positional drift reported.

While the same process appears to be the case in the absence of a visual template (Experiment 2), the perceived errors may appear less explicit and corrective movements of the unseen hand subsequently less pronounced.

It should be noted that the explanation here is speculative. In order to demonstrate this relationship, one would need to monitor deviations by the seen limb on a movement-by-movement basis and then examine whether subsequent movements of the unseen limb were modified to 'correct' for the illusory visual information. The continuous and relatively complex nature of circle-drawing as a task in this study did not allow such an analysis to be easily undertaken.

Nevertheless, such an investigation could be of significant value. In addition to providing a more robust account of the explanation for positional drift observed in the unseen limb, by examining the congruence between the perceived error of the illusory limb and subsequent correction, such an analysis has the ability to track participants' *ownership* of, and *agency* over the illusory limb from moment to moment. This would be significant as to date, assessment of ownership and agency over the illusory limb is limited to retrospective and subjective ratings.

In the following chapter (Chapter 3), an experiment was designed, and an analytical process was developed to address this challenge.

Spatial coupling

As highlighted in the introduction to this chapter, two previous studies examined the impact of mirror visual feedback on bimanual coordination using a circle-drawing task (Franz & Packman, 2004; Metral et al., 2014). Both these studies found the spatial coupling of circles to be enhanced when a mirror was in place. In both experiments reported in this chapter, there was also evidence of mirror visual feedback eliciting greater spatial coupling between the limbs than when the opaque screen was in place. While together, these studies provide fairly compelling support for the effect, does the enhanced spatial coupling denote anything further? In all cases where mirror visual feedback has led to greater spatial coupling, this has been due to the unseen hand making larger movements than in the other condition tested (e.g., when the mirror was replaced with an opaque screen). Under more simple conditions (i.e., no mirror or opaque screen), Franz (2004) reported that the size of circles was modified by manipulating the focus of attention. When participants paid attention to one particular limb, this limb made larger circular movements. This was true for both non-visual as well as visual attention but was most pronounced for the latter. The finding of this chapter that mirror visual feedback also enhanced circle size may in turn, suggest that there was greater attention to the unseen limb in this condition. It has been claimed that mirror therapy enhances attention to the impaired (unseen) limb (Dohle et al., 2009), and the spatial coupling found in the present study seems consistent with this.

Temporal coupling

When unimpaired participants make continuous bimanual circle drawing movements, it is important to recognise that movements are ostensibly coupled such that the hands reach the top and bottom of each circle drawn at broadly the same time (Kelso et al., 1979). However, it is also known that the very small asynchronies that can be present may be modulated by adjusting conditions (Franz et al., 2002; Swinnen et al., 1996). However, the two previous studies that examined the impact of mirror visual feedback on bimanual coordination did not find any reliable related modulation (Franz & Packman, 2004; Metral et al., 2014). That was not the case here. In both experiments reported in this chapter, the presence of mirror visual feedback had a reliable, consistent and intriguing influence on small between-limb asynchronies. Overall, there was a tendency for the dominant (right) limb to lead with a reciprocal non-dominant (left) limb lag. However, when mirror visual feedback was present, this increased the right limb lead when participants experienced a right illusory limb and shifted in the opposite direction (e.g. a reduced right limb lead in Experiment 1 and a left limb lead in Experiment 2) when participants experienced a left illusory limb. This is interesting as these modulations are entirely consistent with what is observed when attention is drawn to the actual limb (Swinnen et al., 1996). In their study, Swinnen et al. (1996) had participants perform bimanual circle-drawing movements while visually monitoring one hand or the other. They too, found a generalised small right-hand lead. Additionally, in their attentional cueing account, they also found that visually monitoring the dominant or non-dominant limb respectively increased or reduced this asynchrony. Consistent with the findings discussed above (temporal coupling), the findings here strongly suggest that mirror visual feedback increases attention to the illusory limb.

Conclusion

This chapter presents two experiments examining the impact of mirror visual feedback on bimanual movements. The findings suggest that a powerful visual illusion *drives* motor control of the unseen limb. Accordingly, the position of the unseen limb was found to drift away from its starting position, with participants seemingly unaware of the relatively large discrepancies between the relative positions of their actual limb and the illusory limb. The positional drift was most apparent when a visual template guided movement. While limitations in the experiments reported here prevented more in-depth analysis, the findings suggest that examining positional drift on a movement-by-movement basis may provide a window to observe an individual's ownership and agency over the illusory limb. In Chapter 3, the aim was to do just this. Additional findings reported here relating to spatial and temporal coupling strongly suggest that mirror visual feedback of an illusory limb enhances attention to the unseen limb. This is important as enhanced attention to the impaired limb is a reported mechanism underpinning the effectiveness of mirror therapy for hemiparesis following stroke.

Chapter 3. Sense of agency over the illusory hand during mirror visual feedback

The current chapter was presented at the 'Society for Neuroscience 2022' conference.

Abstract

During mirror therapy, it is typically considered important for the patient to have ownership and a sense of agency over the illusory limb; that is, they believe the limb they observe in the mirror is their own, and they are the author of its actions. However, measuring these characteristics typically relies on subjective judgments that may be considered unsatisfactory. In contrast, here this chapter aimed to examine ownership and agency over the limb by measuring the kinematic relationship between the two limbs during mirror therapy activity, asking *do participants move their unseen limb in a way that is consistent with the illusory visual information they receive*?

Twenty unimpaired right-handed participants performed 15 s trials of self-paced repetitive aiming movements (between far target and near targets) with a mirror/symmetrical coordination pattern. For the *mirror* condition, the vision was directed towards the far target in the mirror. In the *no mirror* condition, the direction of vision was unchanged, but the mirror was replaced with an opaque screen. The movements of both hands were recorded using motion capture apparatus. Analysis sought to examine the consistency of *corrective* movements to the illusive image with correction angles in each tap.

As the previous chapter (Chapter 2) reported, under these circumstances, the unseen hand may undergo substantial positional drift in the course of a 15 s trial. Here, we plotted the illusory error (generated by the *seen* hand) on each movement, using this to predict the movement trajectory of the unseen hand on the subsequent movement and then comparing this with the actual movement observed. As anticipated, the substantial positional drift of the unseen hand was observed as it made corrective movements consistent with the illusory visual information generated by the seen hand. However, at least once (on average) during each *mirror* trial (7% of all movements), unseen hand movements were observed inconsistent with illusory information. This is interpreted as being indicative of an *illusion break* and diminished ownership and agency over the illusory limb.

Introduction

Mirror therapy is an effective intervention for improving movement and pain of the affected upper limb following hemiparetic stroke (Thieme et al., 2018). It typically involves a mirror being placed in the patient's mid-sagittal plane with the reflective side facing in the direction of their unaffected limb. By then placing the patient's upper limbs symmetrically on either side of the mirror and having the patient direct their vision towards the mirror, the reflected image of the unaffected limb is perceived as the (unseen) affected limb. Patients are therefore provided with visual information suggesting both limbs are *normal* or *unimpaired*; when the unimpaired limb is moved, the patient is provided with visual information from the mirror suggesting the impaired (unseen) limb is also moving. This illusion may deceive the patient into thinking that the limb in the mirror is their "own" limb (McCabe, 2011).

Understanding the nature of the illusion elicited by mirror therapy benefits from a more detailed understanding of how one recognises one's own body; a process referred to by Jeannerod (2006) as *self-identification*. Gallagher (2000) draws a distinction between the sense of *ownership* and the sense of *agency*. In terms of movement, a sense of ownership refers to the recognition that it is one's self that is experiencing it. Applied to mirror therapy, it follows that the participant recognises that the actual unseen hand is experiencing what the hand in the mirror is experiencing. In contrast, a sense of agency refers to the experience that the one is responsible for producing a given movement; that one is its agent. With reference to mirror therapy, having a sense of agency refers to the sense that one is the agent controlling the illusory limb.

When provided with mirror visual feedback (as in mirror therapy) and performing symmetrical bimanual movements, there is a strong tendency for one to have a strong sense of ownership and agency over the illusory limb. Holmes and Spence (2005) showed that the sense of ownership and sense of agency for the illusory limb can be reinforced by symmetrical bimanual movements compared to no movement. They provided different visual exposures to two groups. One group was instructed to gaze at their hands in the mirror and move both hands synchronously and simultaneously (active visuomotor). The other group was asked to gaze at the hand in the mirror in a still motion (passive visual exposure). After observing mirror reflection, both groups were then asked to reach the suggested target with the unseen hand. The greater the discrepancy between the position of the hand shown in the mirror and the position of the actual unseen hand, the higher the reaching mistake. The active visuomotor group showed higher mirror-induced bias, which impacted the accuracy of the following reaching test. Even in the presence of a positional discrepancy between the unseen hand and the illusive hand, the integration of visual and proprioceptive information appeared to have been stimulated. This finding suggests that symmetrical bimanual tasks enhance the sense of ownership and agency.

While performing bimanual movement with mirror visual feedback (as in mirror therapy) typically appears to enhance ownership and agency over the illusory limb, if conflict emerges between movement intention and subsequent sensory feedback, this may weaken or eliminate ownership and agency over the illusory limb (Jeannerod, 2006). Fink et al. (1999) attempted to investigate these issues in a systematic way by examining bimanual movements with and without a mirror. For each condition, participants were asked to rate the *strangeness/peculiarity of their experience* following each condition, providing a subjective measure of psychological conflict. The study also used brain imaging to examine the neural consequences of such conflict. Participants performed bimanual movements (fist opening and closing) under four different conditions. Movements were either congruent (in-phase) or incongruent (out-of-phase); and were performed both with and without a mirror. When there was no mirror, participants directed their vision toward the left hand. For the mirror conditions, the mirror obscured the left hand, but participants directed their vision in the same direction observing the reflection of their right hand. Participant ratings of strangeness/peculiarity were generally very low but increased markedly when they made incongruent bimanual movements with a mirror. Of course, this is the condition where obvious conflict was observed. Interestingly, brain imaging revealed this conflict to be associated with significantly increased activity in the right dorsolateral prefrontal cortex, a subsequent experiment also confirming increased activation in the same area (also on the right) when the laterality of the task was reversed (i.e. when the right hand was obscured by the mirror). These findings appear to highlight the profound effects that a mirror can have in modifying ownership and agency over an illusory limb. The relationship between intention and sense of agency can also be explained through the comparator model (Frith, 2005; Frith et al., 2000), which is an influential theory proposed to explain the sense of agency.

If the comparator model is considered in relation to performing bimanual movements with mirror visual feedback, the unseen hand's action begins with intentions or goals and represents a form of the motor system's desired state (Searle & Willis, 1983). Based on information about the desired state, the motor control system generates a motor command and initiates the movement of the unseen hand. After moving, visual and proprioceptive sensory feedback is received in the unseen hand's new state. Sensory information is used to estimate a new state and compare it to the desired state (Haggard & Clark, 2003; Haggard et al., 2002; Tsakiris & Haggard, 2003). If a visual mismatch between the new and desired states is detected, the same motor control process is repeated until the desired state is achieved by updating the motor command. In this process, the predictive component aids in quickly managing the difference between the desired and actual states (Miall & Wolpert, 1996; Wolpert, 1997). The predictive component is reconstructed based on the previous movement's motor command and current sensory feedback. Accordingly, prediction is an index that determines whether the motor command is properly represented in the movement (motor control) and whether the state corresponds to the intention (sense of agency). Therefore, a comparison of predicted and actual states of the unseen hand can be used to determine a sense of agency (Sato & Yasuda, 2005). If it matches, one may experience a sense of agency; if it does not match, one may not experience a sense of agency (Moore, 2016).

As Moore (2016) explains, measuring agency can be difficult. Previous related measures have primarily consisted of subjective ratings via questionnaires. Although the number of items, scoring scales, and precise questions asked by researchers vary, the core contents are linear with the concept. The sense of agency questions asked participants whose movement they believed was the movement in the mirror. While scorings varied, the Likert scale was mainly used to show degrees of agreement on positive scales and degrees of disagreement on negative scales to ultimately collect the matter of agreement with the feeling experienced during the experiment.

Asking directly about the participant's illusion experience (explicit measure) is an intuitive way to measure the sense of agency. This explicit measure, however, is difficult to convey objectively or precisely; it simply suggests how much the participants believed the illusion during the experiment and quantifies their feelings regarding this (Moore, 2016). The use of questionnaires is also vulnerable to issues such as delays between action and outcome judgments, reducing their reliability. To overcome the shortcomings discussed, using the comparator model and inferring a sense of agency from this (implicit measure) can be considered. Sense of agency during mirror vision feedback can be objectively described using the comparator model by predicting the movement of the hand hidden behind the mirror with the seen hand reflected in the mirror and comparing how the actual unseen hand moved based on the illusive information.

The potential of using implicit measures as an alternative to explicit measures during mirror visual feedback was demonstrated by Tajima and colleagues (2015). They compared the results of implicit and explicit measures by running two separate experimental sessions. In the first session, they found a proprioceptive drift area from the unseen hand (implicit measure). Participants were asked to point and fix the index finger of the seen hand toward the mirror, and the index finger of the unseen hand to point freely on the opposite side of the mirror. Whenever the participant freely changed the position of the unseen hand, they were asked if they thought the position of the seen hand and the position of the unseen hand were the same. Based on the participants' "yes" or "no" responses, a boundary was drawn dividing the areas.

The area where participants said "yes" was designated as the proprioceptive drift area. In the second session, the same procedure was used for the seen hand, but the participants were asked to complete a questionnaire (16 items) about their sense of agency in 13 pre-specified unseen hand positions (explicit measure). Following the two sessions, the proprioceptive drift area and the spatial mapping drawn from the questionnaire were compared, and it was discovered that the two results overlapped. This demonstrates that spatial tracking is conceivable in the drifted unseen hand and that it may be possible to investigate the sense of agency by examining motor behaviour (implicitly) rather than by asking questions (explicitly).

In our previous chapter, as participants performed the bimanual circle-drawing task, we observed the positional drift of the unseen hand when movements were made with mirror visual feedback. We speculated that this drift occurred as a result of participants demonstrating a sense of agency over the illusory limb and making 'corrective' movements based on the perceived position of their unseen hand. Since the continuous task lacks a distinct beginning or end, it was challenging to establish the link between the seen hand and the unseen hand (on a movement-by-movement basis) and stipulate the precise moment of error and correction.

This chapter aimed to develop an objective method of measuring this sense of agency, using a novel bimanual repetitive aiming task to track the relationship between the limbs during mirror visual feedback. It was sought to measure the relationship between the perceived error of the unseen hand and the subsequent correction of the unseen hand on a movement-by-movement basis. The present study approach was also designed to identify whether there was evidence supporting the idea of an 'illusion break'; this would be inferred where there was a failure to move the unseen hand in a manner consistent with the perceived error.

Methods

Participants

Twenty (four male) participants from the undergraduate student body at the University of Birmingham volunteered to take part in the study. All self-reported being right-handed, and this was confirmed by the Edinburgh Handedness Inventory (EHI) – short form (Veale, 2014) with a score of 61 or higher (Milenkovic & Dragovic, 2013); mean score = 93.4 $\pm$ 11.3. All participants were unimpaired and were naïve to the purpose of the study. The study was approved by the University of Birmingham's Science, Technology, Engineering and Mathematics Ethical Review Committee. Participants provided written informed consent prior to taking part.

Apparatus

The experiment was conducted in the Motor Cognition Laboratory, housed within the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. Limb movements were recorded at a sampling rate of 200 Hz using three motion capture cameras (Miqus, Qualisys Ltd., Sweden) to track small spherical markers (6.5 mm diameter) attached to the nail of each index finger using double-sided sticky tape. A portrait-oriented Perspex mirror (53cm X 36cm) was placed perpendicular to the table and aligned to the participant's mid-sagittal plane using two small bespoke wooden mounts. A printed template on a piece of high-quality (thick) A1-sized paper was fixed on the table and filled the workspace for the experiment. Earlier work (Chapter 2) highlighted that if there is another visible mark on the paper besides the target, it can be used as an additional visual reference when correcting movements. To prevent the paper from getting dirty or torn, it was laminated and was checked regularly to ensure there were no marks on it. As can be seen in Figure 3.1.1, a line was drawn in the middle of the template to mark where the mirror was placed. Based on this line, two dots were drawn on each side 20 cm away from the line. The two dots (1 cm diameter) functioned as targets to guide the reciprocal bimanual movements. The near target (closer to the participant) was positioned 10 cm from the table edge; the far target was positioned 20 cm from the near target and 30 cm away from the body.

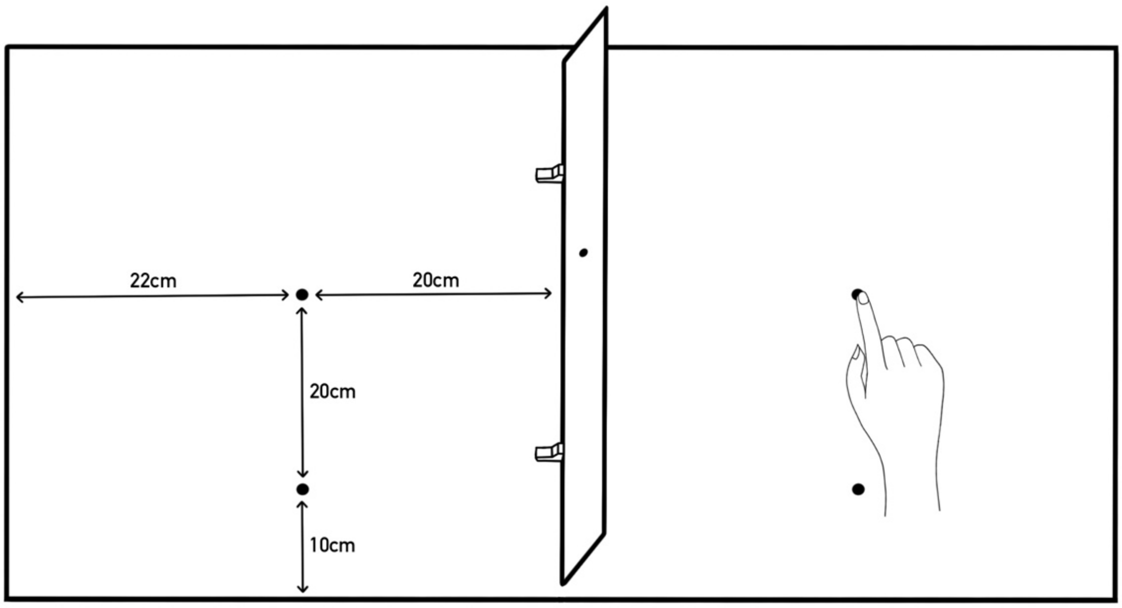


Figure 3.1.1 Experimental set up. The mirror was placed perpendicular to the table and aligned to the participants' mid-sagittal plane. The template was placed under the mirror and fixed to the table. On the template, two dots (1cm diameter sized) were drawn on each side 20cm away from the mirror. Of the two dots on either side, the near target and the far target were defined according to the distance from the participant. The near target was 10cm away from the table edge; the far target and the near target were drawn 20cm apart vertically.

Task, design, and procedure

During the study, each trial required participants to make repeated discontinuous movements with their upper limbs, their index fingers moving between the near and far targets with both hands for 15 seconds. The frequency of movements was not controlled strictly, but participants were instructed to complete one cycle (i.e. from near target to far target to near target) per second (see Figure 3.1.2).

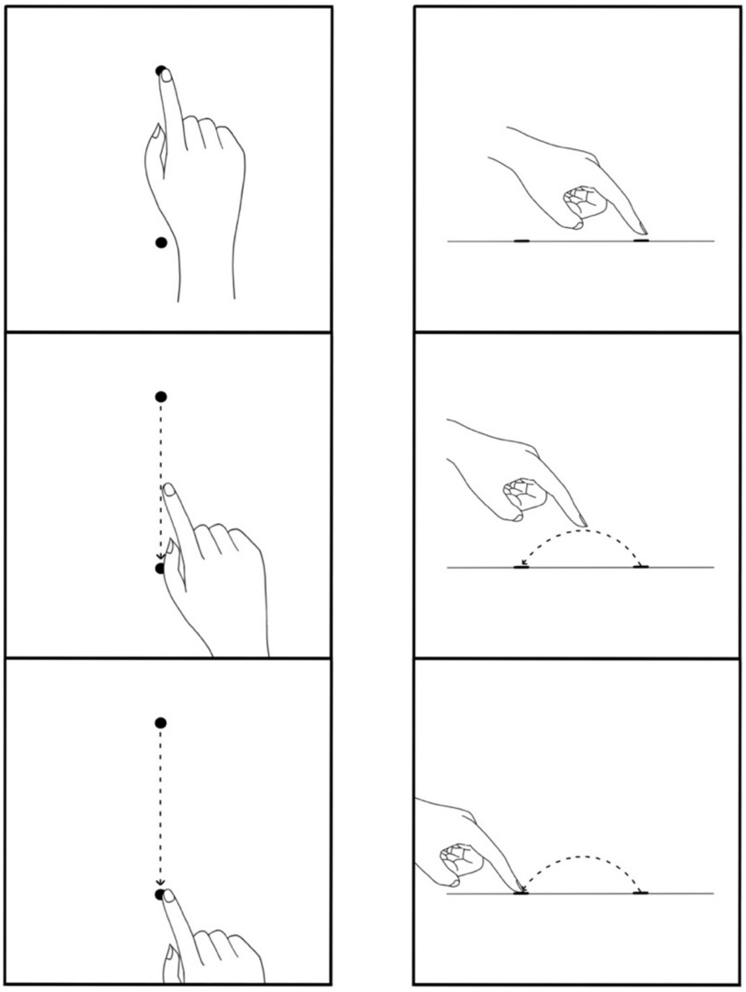
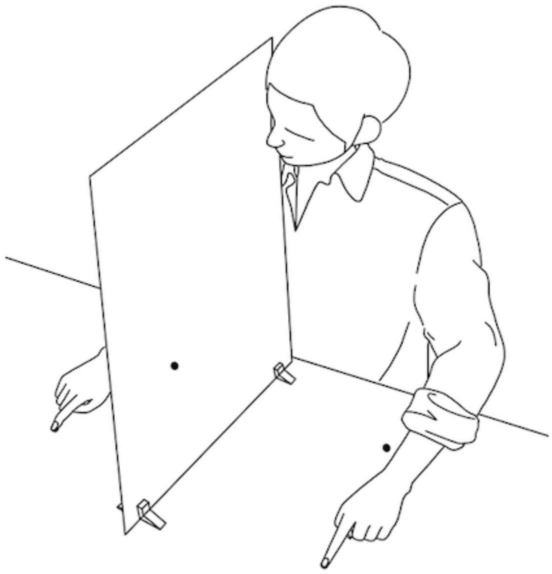


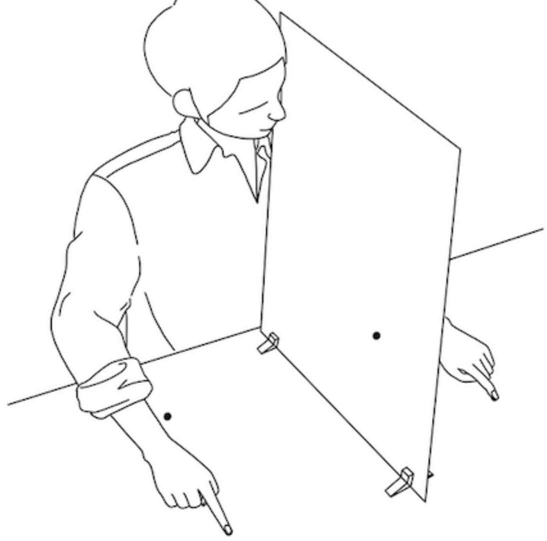
Figure 3.1.2 Repeated bimanual reaching task between near and far targets. Top view (left column) and side view (right column) of the task. The initial position of the trial was on the far target. At the "go" signal, both hands were moved towards the near target. After pointing at the near target, the fingers moved back to the far target. This reciprocal reaching task was repeated until the "stop" verbal cue.

Each trial began with the participant's index fingers positioned on the far target. The examiner helped position the (unseen) hand behind the mirror. To prevent participants from looking at the position of their 'unseen' hand between trials, both hands were placed under the table following the completion of every trial. If the participant touched the mirror or wooden mount with the unseen hand during the trial, the trial ended at that point.

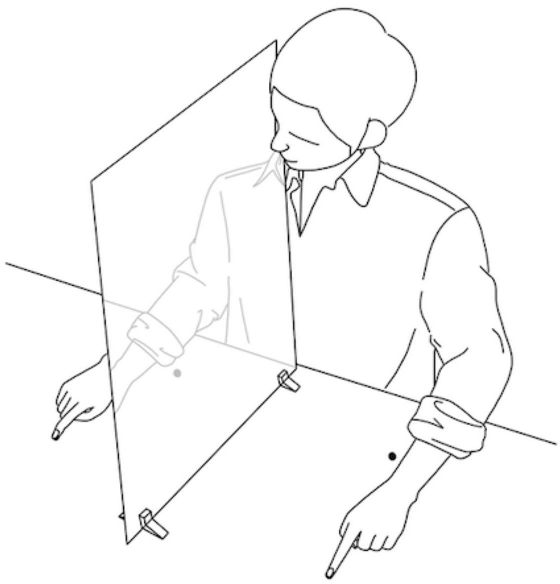
Participants performed 40 trials during the experiment, and there were four conditions; participants completed ten trials per condition. The four conditions (see Figure 3.1.3) were as follows; left hand visible without a mirror (*Left Vision*), left hand visible with a mirror (*Left Mirror*), right hand visible without a mirror (*Right Vision*), and right hand visible with a mirror (*Right Mirror*). Conditions were randomised across trials. For the *Mirror* conditions, the reflective surface of the mirror was on the same side as the participant's head and the participant was instructed to direct their vision to the reflection of the top target in the mirror. For the *No mirror* conditions, the mirror was positioned the opposite way around so that the opaque surface was on the same side as the participant's head. For these trials, the participant was instructed to direct their vision toward a fixation cross that was placed on the opaque surface of the mirror spatially consistent with the position of the top target in the *Mirror* conditions.



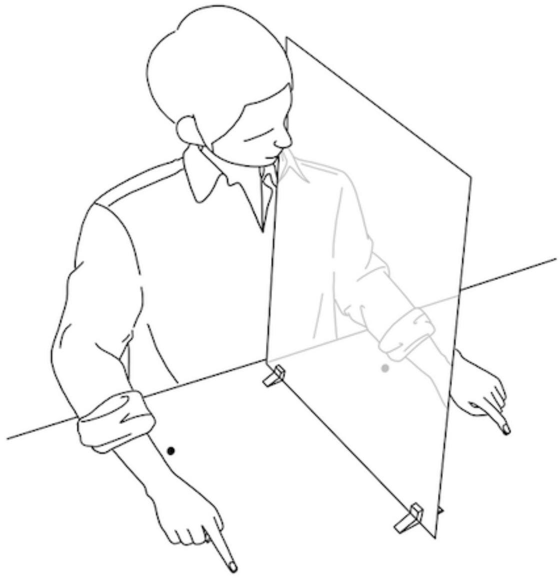
3.1.3-a Left Vision



3.1.3-c Right Vision



3.1.3-b Left Mirror



3.1.3-d Right Mirror

Figure 3.1.3 Experimental conditions. Four conditions were made by combinations of the Head side (Left, Right) and Mirror (Mirror, Vision) variables. The Head side was defined based on which side the head is placed relative to the mirror, and the Mirror shows whether the participant was facing the mirror or the opaque screen. When the mirror was present, participants were instructed to focus their visual attention on the far target in the mirror. When the mirror was removed, a point on the opaque screen in a position congruent with the mirror condition became the focus for visual attention.

Before commencing the experiment, participants filled out the EHI-short form questionnaire and read the written instructions regarding the procedure. Any accessories on their hands and wrists were removed, and any questions regarding the procedure were answered. Participants completed a practice trial once for each condition before the actual task. To get used to the aiming pace, a metronome was set to 120Hz during practice. Once the experimental trials began, the researcher provided verbal “go” and “stop” signals to indicate the start and finish of trials. Between the trials, there was a short break and a scheduled break after 20 trials.

Data analysis

Kinematic data were exported from the motion capture system and analysed via bespoke software (Matlab 2021b, Mathworks Inc., Natick, MA, USA). Signals were rectified and filtered with a 4th-order low-pass Butterworth filter using a cut-off of 20 Hz.

Results

Overview

The present chapter investigated the sense of ownership and agency by examining the kinematic relationship between the hands during mirror visual feedback. In short, the aim was to observe whether the unseen hand moved in a way consistent with the illusory visual information generated. The process employed to achieve this is described in the following five sections.

(1) The first section checked to see if the unseen hand's positional drift from our previous study appeared in this experiment. The incidence of drift demonstrated that the error of the seen hand was continuously corrected by the unseen hand. Interestingly, the participants

commented that there were times when they doubted the illusion throughout the trial. The kinematic link between the two hands was used to attempt an objective demonstration of the moment of doubt.

(2) Section 2 began the investigation of the moment of doubt by focusing on the drift that happened at the far target. This section attempted to examine the directional component of corrective movement based on the causes of drift described above. Mirror visual feedback was shown to induce more correction in the azimuthal direction than in the radial direction. The directional correction rate illustrated the correction characteristics while presenting a few variables to consider when analysing each movement.

(3) Section 3 suggested a novel analysis approach (correction angle) that considers the extent of the correction at the far target. Also verified the rationale behind comparing the seen hand's error with the subsequent unseen hand's movement. The comparison of the seen hand's correction angle (PCA) and the subsequent unseen hand's correction angle (ACA) was found to be efficient. Still, it was determined that an extra analysis tool should be introduced to examine each movement.

(4) As a first supplementary tool, after overlapping PCA and ACA, we tried to distinguish how accurately the target in the mirror (predicted target) was aimed. The shape and size of the threshold were suggested from the aiming variability formed around the predicted target. A circular threshold around the predicted target played a role in distinguishing aimed points that moved consistently with the illusion.

(5) Based on the previous sections, three criteria were established to ultimately identify the movements that were inconsistent with the illusion. First, aimed points located close to the far target were controlled with a circular threshold. Second, aimed points with corrective

intention were controlled by adjusting the aiming arc based on a circular threshold created around the predicted target. Finally, the aimed points that went opposite to the predicted corrective direction were chosen. Based on these three criteria, how many aimed points per trial moved inconsistently with the illusion was counted. Illusion inconsistent movements were defined as the moment when the sense of agency was disrupted.

Section 1: The unseen hand showed marked positional drift during trials of the mirror conditions

Background

As highlighted in Chapter 2 of this thesis, the most striking observation from the experiments reported was the substantial positional drift of the unseen hand while performing bimanual movements with mirror visual feedback. It appeared that the 'corrective' movements made by the unseen hand in response to observing small errors of the seen hand reflected in the mirror accumulated, leading to the marked positional drift observed during related trials. However, clearly identifying this relationship while tracking the relationship of both hands during continuous bimanual circle drawing would be very challenging. For instance, comparing the unseen hand's corrective movements to the position of the seen hand's error is difficult to define as neither the start nor endpoint in each cycle is specified.

In order to be able to explore the relationship between the movement of the seen hand and any subsequent corrective movements with the unseen hand, this new task was developed that addressed some of the issues above. Rather than using a *continuous* bimanual task like circle drawing, a *discrete* bimanual task was designed which allowed for the comparison of hand positions at defined points, both spatially and temporally.

In this experiment, a bimanual task was designed requiring the participant to make repetitive mirror symmetrical aiming movements between clearly defined near and far visual targets. Based on the results from the previous experiment together with additional informal pilot testing, we expected to see a similar positional drift of the unseen hand for conditions involving mirror visual feedback. However, in this case, the clearly defined targets provided a means and opportunity to track the unseen hand's corrective movement in response to the seen hand's error on a movement-by-movement basis.

Therefore, this first section aimed to capture and measure any positional drift observed in a manner consistent with the previous chapter.

Data analysis

In this section, the main variables of interest were *positional drift from the target (far and near)* and S*traight-line distance of movements between targets*. *Positional drift from the far target* was the primary outcome, with *positional drift from the near target* and *straight-line distance* as secondary outcomes.

Dependent variables were defined accordingly:

Positional drift from the far target – The furthest points touched for aiming movements to the far target in each trial of all participants were found and calculated the straight-line length to the far target.

Positional drift from the near target – The furthest points touched for aiming movements to the near target in each trial of all participants were found and calculated the straight-line length from the near target.

Straight-line distance - The direct distance (i.e. 2-dimensional straight-line) between the touch points made to the near and far targets.

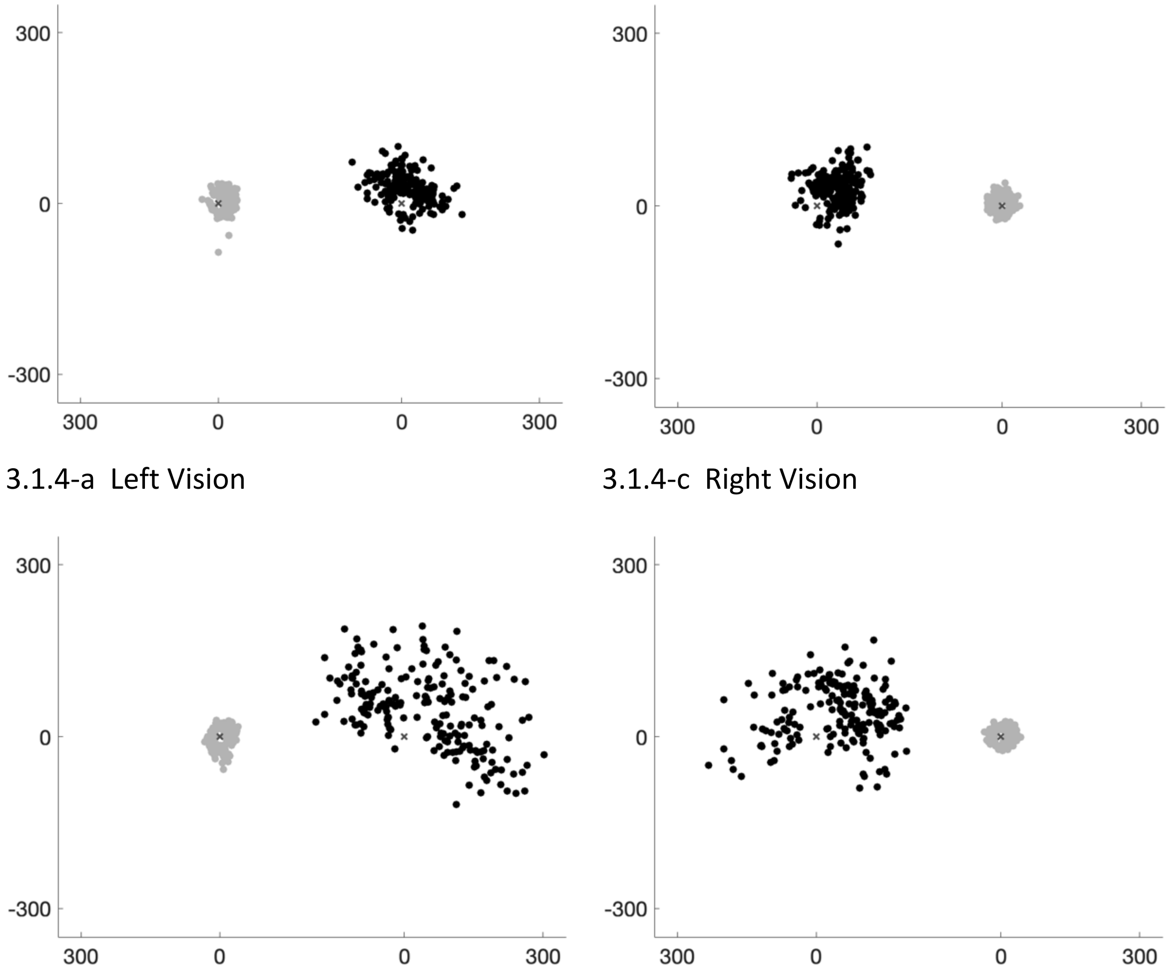
Statistical analysis

Data were analysed by using SPSS (IBM SPSS Statistics, Version 27.0. Armonk, NY, USA) and all normality checks were conducted. The data were normally distributed and appropriate for analysis using parametric tests. For each of the above dependent variables, individual mean values were calculated. Data were subsequently analysed via a 2 × 2 × 2 (*Head side* [left, right] × *Mirror* [mirror, opaque screen] × *Hand* [seen, unseen]) analysis of variance (ANOVA) with repeated measures. The interactions between simple effects were analysed with multiple comparison subject to Bonferroni correction. The threshold for statistical significance was set to $p < 0.05$.

Section 1 Results

Positional drift from the far target

Figure 3.1.4 shows the points representing the furthest point touched in each trial from the far target; for both hands and for all conditions. Across the experiment, this distance was greater when the mirror was in place (mean = 73.72 $\pm$ 61.15mm) than when replaced by an opaque screen (mean = 41.21 $\pm$ 21.91mm), leading to a significant main effect of *Mirror*, $F(1,19) = 153.03$, $p < 0.001$, $\eta_p^2 = 0.890$. Additionally, the *unseen* hand (mean = 92.88 $\pm$ 39.67mm) drifted from the far target to a larger extent than the *seen* hand (mean = 22.05 $\pm$ 1.02mm), $F(1,19) = 446.43$, $p < 0.001$, $\eta_p^2 = 0.959$. However, *Head Side* x *Mirror*, $F(1,19) = 9.60$, $p = 0.006$, $\eta_p^2 = 0.336$, *Mirror* x *Hand*, $F(1,19) = 165.40$, $p < 0.001$, $\eta_p^2 = 0.897$, and *Head Side* x *Mirror* x *Hand*, $F(1,19) = 9.94$, $p = 0.005$, $\eta_p^2 = 0.344$, interactions suggested a more complex relationship between factors. As can be seen in Figure 3.1.5, the interaction is explained by the impact of the *mirror* on the *unseen hand*. Accordingly, the positional drift of the *seen* hand was comparable regardless of whether the mirror was in place or not, $F(1,19) = 0.17$, $p = 0.684$, $\eta_p^2 = 0.009$. However, the positional drift of the *unseen* hand was significantly greater when the mirror was in place, $F(1,19) = 9.78$, $p = 0.006$, $\eta_p^2 = 0.340$.



3.1.4-a Left Vision

3.1.4-c Right Vision

3.1.4-b Left Mirror

3.1.4-d Right Mirror

Figure 3.1.4 Positional drift from the far target. Dots represent furthest point from the far target on every trial as a function of the Head side, Mirror and Hand. Seen hand dots are colour-coded in grey, and the unseen hand dots are in black. Far targets on both sides are marked as 'x'. This figure illustrates that in mirror conditions, the unseen hand's furthest points from the far target are farther away than in vision conditions. Scale values are in millimetres.

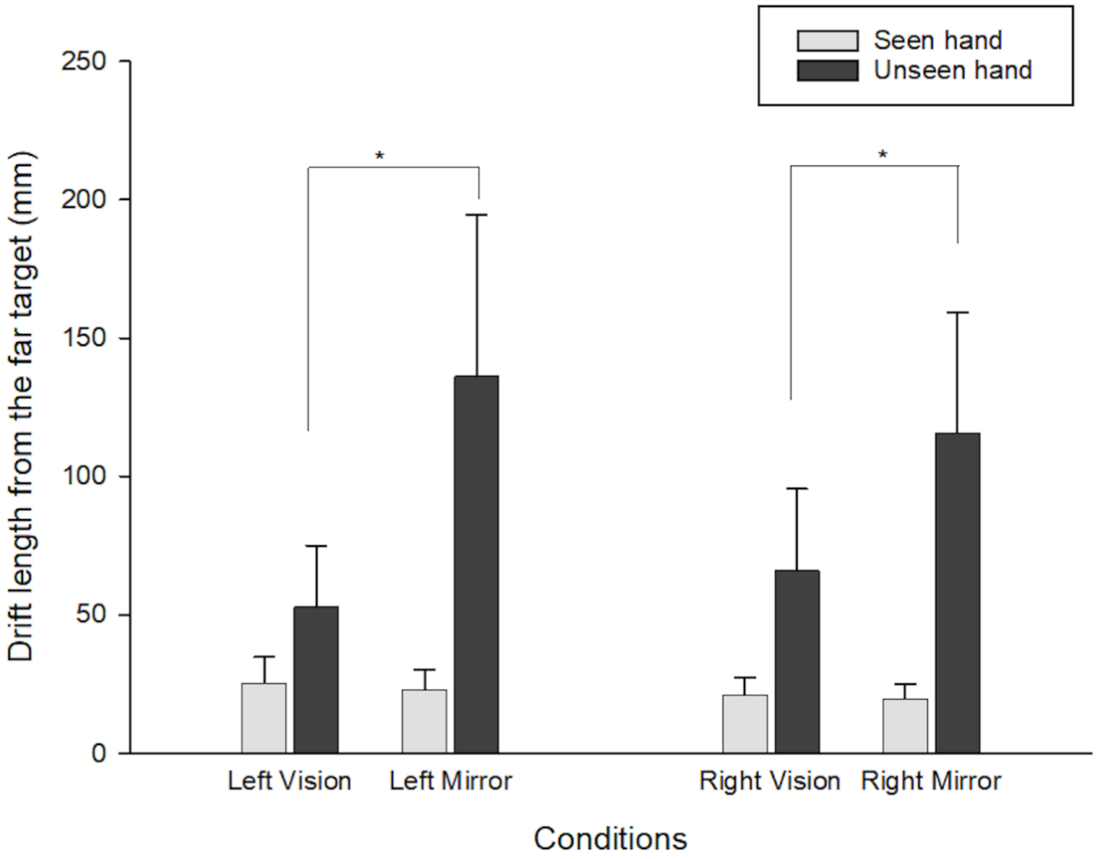
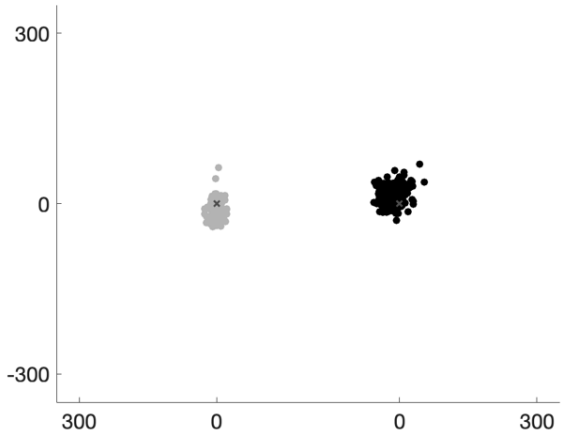


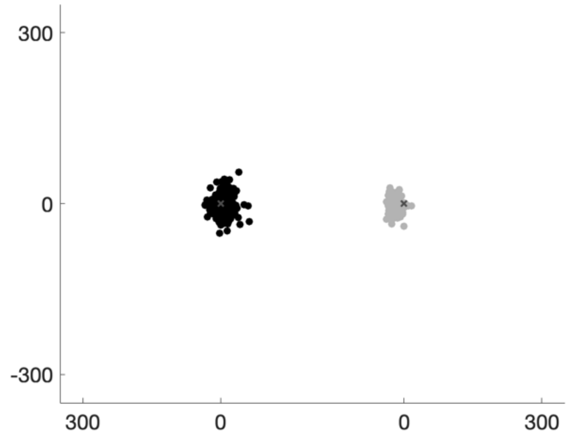
Figure 3.1.5 Mean drift length from the far target as a function of the Head side, Mirror and Hand. This bar chart shows that in mirror conditions, the unseen hand's mean drift length from the far target is longer than in vision conditions. Error bars denote standard error and asterisks denote statistical significance.

Positional drift from the near target

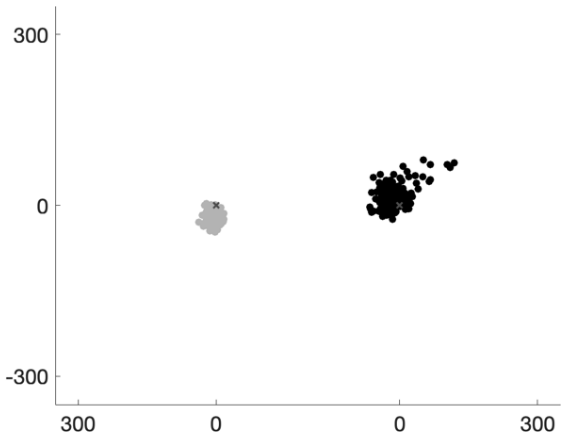
Figure 3.1.6 shows the points representing the furthest point touched in each trial from the near target; for both hands and each condition. Figure 3.1.7 shows the related group mean values. Across the experiment, the distance for the *unseen* hand (mean = 33.47 ± 3.28mm) was significantly greater than the distance for the *seen* hand (mean = 15.95 ± 1.88mm), leading to a significant main effect of *Hand,* $F(1,19) = 51.09$, $p < 0.001$, $\eta_p^2 = 0.729$. As can be seen in Figure 3.1.7, these differences were maintained in all conditions. Additionally, the positional drift of the unseen hand was comparable regardless of whether the mirror was in place or not, $F(1,19) = 1.59$, $p = 0.222$, $\eta_p^2 = 0.077$.



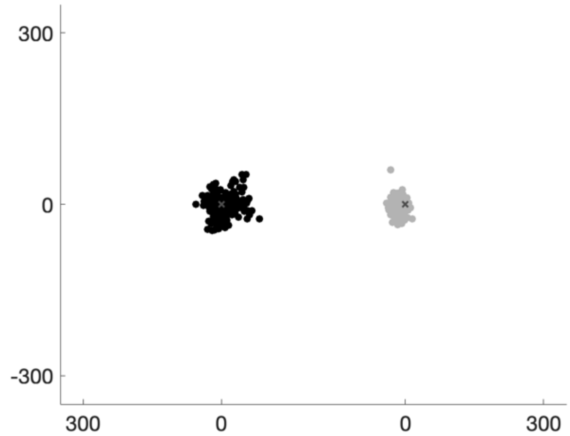
3.1.6-a Left Vision



3.1.6-c Right Vision



3.1.6-b Left Mirror



3.1.6-d Right Mirror

Figure 3.1.6 Positional drift from the near target. Dots represent furthest point from near target on every trial as a function of the Head side, Mirror and Hand. Seen hand dots are colour-coded in grey and the unseen hand dots in black. Near targets on both sides are marked as 'x'. This figure illustrates that the unseen hand's furthest points from near target of all conditions are located similarly. Scale values are in millimetres.

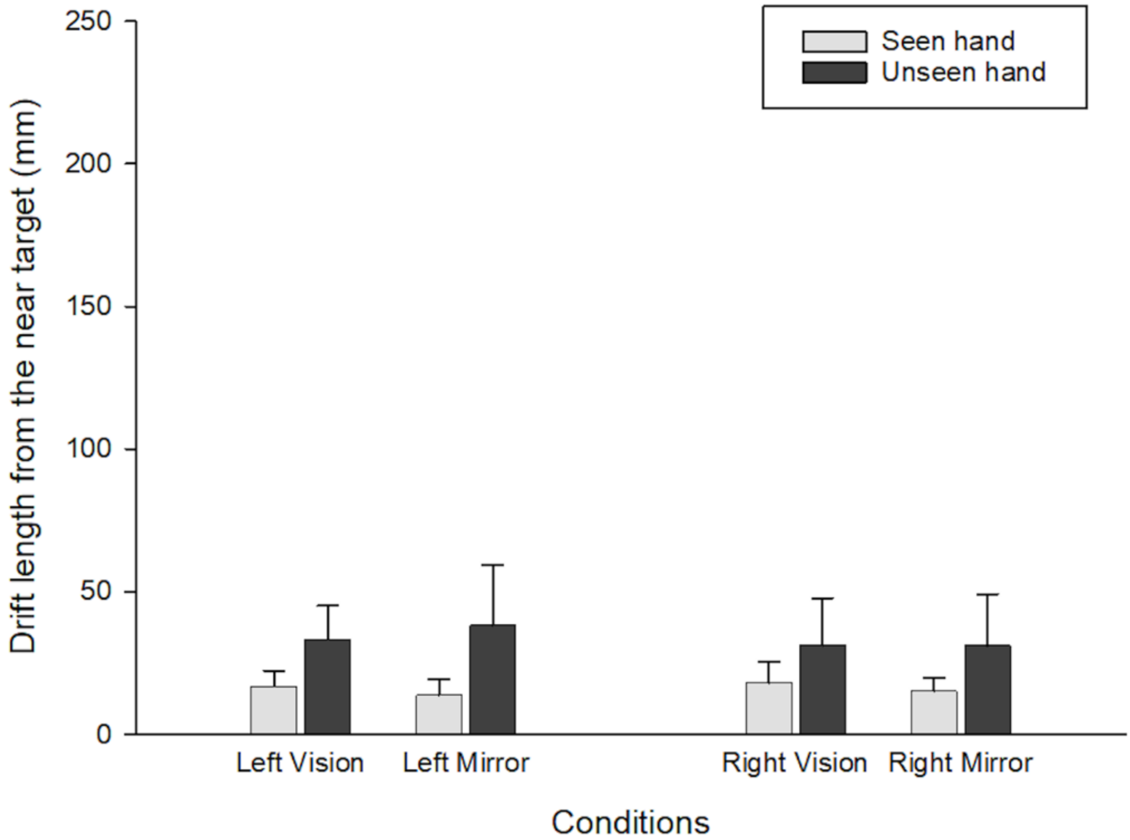


Figure 3.1.7 Mean drift length from the near target as a function of Head side, Mirror and Hand. This bar chart shows that the unseen hand's mean drift length from the near target of the mirror conditions and vision conditions are comparable. Error bars denote standard error.

Straight-line distance

Across the experiment, the mean straight-line distance was longer when the mirror was in place (mean = 199.35 ± 18.87mm) than when replaced by an opaque screen (mean = 191.58 ± 14.78mm), leading to a significant main effect of *Mirror*, $F(1,19) = 20.16$, $p < 0.001$, $\eta_p^2 = 0.528$. Additionally, the *unseen* hand (mean = 197.23 ± 21.93mm) had a significantly longer distance than the *seen* hand (mean = 192.70 ± 11.04mm), $F(1,19) = 6.44$, $p = 0.021$, $\eta_p^2 = 0.264$. However, a *Mirror* x *Hand*, $F(1,19) = 41.52$, $p < 0.001$, $\eta_p^2 = 0.698$, interaction suggested a more complex relationship between factors. The results of the complex interaction are shown in Figure 3.1.8. When the mirror was in place, the unseen hand's straight-line distance was longer than in the *vision* condition, *Left head side*, $F(1,19) = 24.13$, $p < 0.001$, $\eta_p^2 = 0.573$, *Right head side*, $F(1,19) = 19.34$, $p < 0.001$, $\eta_p^2 = 0.518$.

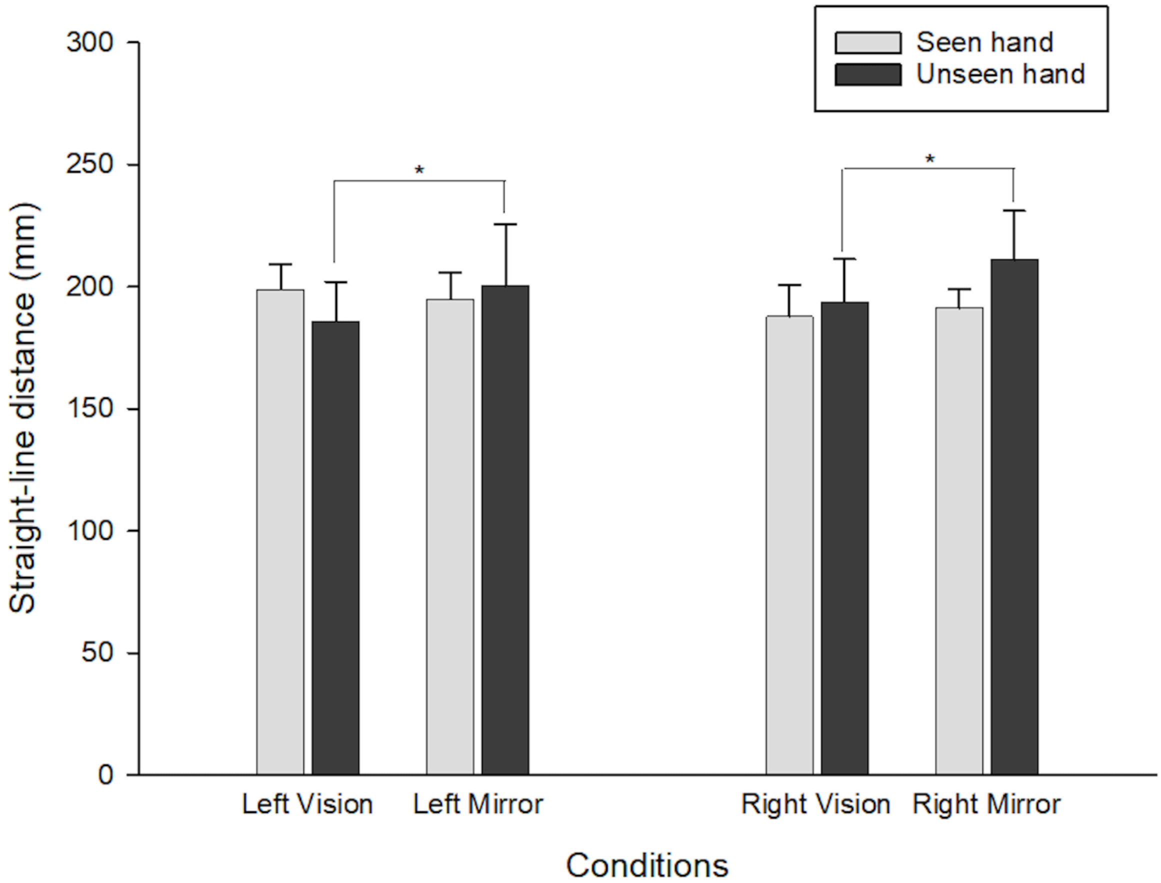


Figure 3.1.8 Mean straight-line distance (from near target aimed position to far target aimed position) as a function of Head side, Mirror and Hand. This bar chart shows that the mean straight-line distance of the unseen hand was longer in mirror conditions than in vision conditions. Error bars denote standard error, and asterisks denote statistical significance.

	Positional drift from the far target (mm)		Positional drift from the near target (mm)		Straight-line distance (mm)	
	Seen hand	Unseen hand	Seen hand	Unseen hand	Seen hand	Unseen hand
Left Vision	24.59 (7.83)	53.19 (22.47)	16.77 (5.41)	33.25 (11.53)	198.19 (9.74)	184.87 (16.20)
Left Mirror	22.89 (7.32)	136.37 (58.29)	13.74 (5.61)	38.18 (20.54)	194.18 (10.58)	200.90 (25.81)
Right Vision	21.06 (6.37)	66.00 (29.43)	18.07 (7.35)	31.31 (16.07)	187.16 (13.16)	192.11 (16.40)
Right Mirror	19.64 (5.54)	115.95 (43.37)	15.20 (4.50)	31.15 (17.42)	191.29 (7.70)	211.04 (20.06)

Table 3.1.1 Mean (and standard error) values of dependent variables in result section 1.

Section 1 Discussion

This section examined the distance that the participants' hands moved away from the targets during all conditions. Comparable behaviour to the previous experiments in this thesis (i.e. Chapter 2) was observed. When a mirror was present, there was significant positional drift of the unseen hand. The positional drift was thought to be produced by the accumulation of consecutive unseen hand corrections following the small seen hand's error, and this appears to have occurred in this experiment as well. While the continuous task made it difficult to investigate the relationship between the seen and unseen hands, the discrete task used in this experiment made it simple.

Data was collected from 20 individuals in this experiment, which was higher than the number of participants in the previous chapter, therefore it was thought to have sufficient power to investigate the influence of mirrors on positional drift. However, a post-hoc power analysis was carried out for this experiment to ascertain whether the sample size of the experiment was sufficient because the bimanual circle drawing task that was given in the prior experiment was replaced with a repetitive reaching task. With twenty participants, positional drift at the far target caused by the mirror demonstrated 100% power; with just two participants, this effect demonstrated 99.7% power.

It is noteworthy that marked positional drift of the unseen hand was only observed in relation to the far target. Conversely, the mean drift lengths from the near target were comparable in all conditions. This suggests that visual attention to the far target enhanced the visual capture (Lohse et al., 2014; Posner, 1980). We had two targets on each side and instructed the participants to gaze only at the far target during the trial. This instruction is likely to have highlighted errors in relation to the far target to be detected, and it was presumably these errors that were repeatedly corrected for.

With mirror visual feedback, the distance in the unseen hand became longer than in vision conditions, while the distance in the seen hand was comparable. The increased distance of the unseen hand during mirror visual feedback seems to be related to the result of positional drift. Participants mostly aimed close to the near target but failed to do so for the far target. As the touched position in the far target changed, the distance increased. This distance difference between the seen hand and unseen hand is taken into account when comparing the illusory movement and the unseen hands' movement in section 4.

Post-experimental comments from the participants revealed that there were moments of doubt about illusory information. Feedback such as "confused," "I felt as if something was going against my will," and "I want to see where my hand was behind the mirror" were expressed following the mirror trials in this experiment. These comments suggest that there was a doubting moment during the participant's illusion experience. This caught our attention and led us to assume that the sense of agency may have been disrupted during mirror visual feedback.

The doubting moment for mirror illusion may have occurred because of the explicit target. In Chapter 2, it was suggested that the visual template played a role in increasing the drift of the unseen hand, and the explicit target of this experiment seems to have played the same role. However, the explicit target would have been used as a reference to retrieve the participant's hand position in each aiming attempt. As the attention was on the unseen hand, there does not appear to be any recognition that the seen hand is missing the target and therefore no correction of this. Participants would have been able to clearly perceive the error between the target and the illusive hand whenever aiming at a far target. This could have provided accurate corrective information for the next movement and at the same time, predicted the subsequent aiming position. According to the comparator model, if the predicted hand position and the observed hand position on the next movement do not match, the participant may have doubts about the illusion, and the subjectivity for the illusive hand may be disrupted.

To summarise, repetitive aiming induced positional drift under mirror visual feedback, like with continuous circle drawing. The task of repeatedly aiming towards an explicit target induced drift, but it appears to have caused the participants' doubt on the illusion in this study.

The moment of doubt can be the moment when the unseen hand does not correct according to illusory information. The cause of positional drift provides a kinematic relationship to the corrective movement of the unseen hand in the mirror condition. Therefore, the next section aimed to explore the unseen hand's corrective movement by comparing the movement of the subsequent unseen hand according to the error of the seen hand. The directional component of the correction was explored by separating it into azimuth (left/right) and radial (up/down) views for aimed points at the far target.

Section 2: Correction is weighted in azimuthal direction during trials of the mirror conditions

Background

The previous section (Section 1) showed how there was a strong tendency for the unseen hand to spatially drift away from the target in mirror conditions, particularly for some trials. As in the previous chapter (Chapter 2), this positional drift appeared to be the result of participants making small *corrective* movements of the unseen hand in response to mirror visual feedback of the seen hand. While each individual *corrective* movement may be relatively small, these then appear to accumulate during repetitive movements, leading to the substantial drift observed across the 15s of some trials.

Rather than simply assuming this explanation, the precise targets in this experiment afforded the opportunity to examine these *corrective* movements *within* trials. Accordingly, following our hypothesis, it was possible to measure the error of the seen hand on any given movement (*x*) and subsequently measure the corrective movement of the unseen hand on the following movement (*x+1*). This finer-grained analysis provided the opportunity to confirm the basis for the observed drift. In addition, by examining the consistency with which the unseen hand modified its movement in response to the mirror visual feedback, this analysis also promised to offer insight into the participants' agency over the illusory hand.

In order to achieve this, the relationship between the seen hand and the unseen hand was examined on a movement-by-movement basis, measuring the error of the seen hand on a given movement and subsequently measuring the *correction* of the unseen hand on the subsequent movement. The seen hand's error for any given movement (*x*) was measured as an *absolute* error between its tap position and the coordinates of the far target. The subsequent corrective movement of the unseen hand was measured as the *relative* correction based on the difference in its position on movement *x* and its subsequent position on the following movement (*x+1*); see Figures 3.2.1 and 3.2.2.

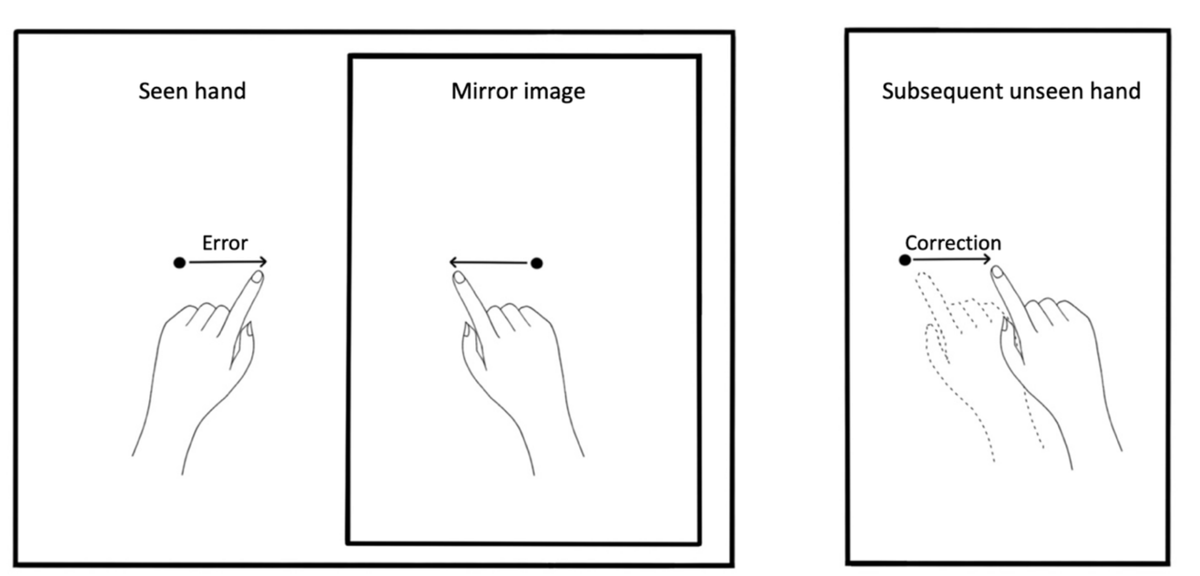


Figure 3.2.1 A schematic illustration of the unseen hand's corrective movement according to the seen hand's error in the azimuthal direction. This figure shows a potential situation of correction in the left mirror condition (seen hand: left hand, unseen hand: right hand). In the figure, the left seen hand taps more to the right side than the far target. The error of the seen hand is inverted mirror-symmetrically, ending up looking like the error of the unseen hand (illusion). The unseen hand in the mirror is on the left side of the target, causing the subsequent unseen hand to make a corrective movement more to the right. In the same way, if the seen hand is tapped to the left, the subsequent unseen hand makes a corrective movement to the left. In the right mirror condition, the same principle applies in the corrective movement of the unseen hand.

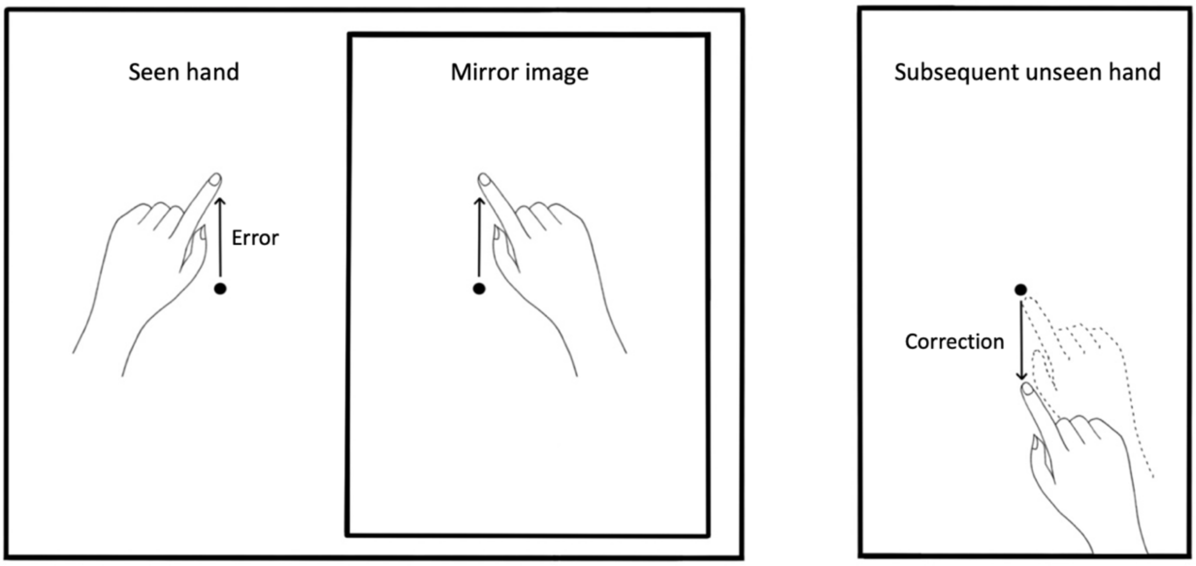


Figure 3.2.2 A schematic illustration of the unseen hand's corrective movement in reaction to the seen hand's error in the radial direction. This figure shows a potential situation of correction in the left mirror condition (seen hand: left hand, unseen hand: right hand). In the figure, the left seen hand taps above the far target. The error of the seen hand is inverted mirror-symmetrically, ending up looking like the error of the unseen hand (illusion). Then, the following unseen hand tap position tries to go lower than the previous one. In the same way, if the seen hand taps below the far target, the following unseen hand tries to tap higher than the previous tapped position. In the right mirror condition, the same principle applies in the corrective movement of the unseen hand.

In taking this approach to analysis, it is important to recognise how the direction of the error in the seen hand determines the perceived direction of the error of the unseen hand via mirror visual feedback. For example, the relationship between these two is different depending on whether the error of the seen hand is in the azimuth (i.e. left-right) or radial (i.e. near-far) direction. An azimuthal error of the seen hand in a given direction is detected as an error by the unseen hand in the *opposite* direction (i.e. the relationship is mirror-symmetrical); if the seen hand misses the target to the *left*, it is perceived as an error in the unseen hand to the *right*. The result of this is that, while the error would be resolved by a corrective movement of the seen hand to the right, providing the illusion is intact, it elicits a *corrective* movement of the unseen hand to the left (i.e. in the opposite direction). This is not the case for radial errors. If the seen hand misses the target by reaching too far, this is perceived as a reciprocal error in the unseen hand (i.e. it has over-reached). Consequently, while the error would be resolved by a smaller movement of the seen hand, a smaller movement is elicited for the unseen hand (i.e. in the same direction), providing the illusion is intact. In this respect, the relationship between the limbs with regard to radial errors may be considered to be parallel.

This section aims to investigate the direction of the unseen hand's *corrective* movement based on the illusory visual information available to the participant. This was achieved by comparing the seen hand's absolute error to the unseen hand's relative correction in two directions (i.e. azimuthal and radial).

Data analysis

The main variable of interest was the *directional correction rate*.

Directional correction rate - For each trial and for all participants, the directional correction rate was calculated by comparing the number of movements made by the unseen hand that were either directionally consistent or inconsistent in terms of *correction* based on illusory visual feedback. These comparisons were made separately for the azimuthal and radial directions. In the azimuthal direction, the absolute error of the seen hand and the consistency in the relative correction direction were investigated in the left and right directions (see Figure 3.2.1), and the consistency in the near-far direction was investigated in the radial direction (see Figure 3.2.2). A 100% rate of directional correction rate would mean that all movements were directionally consistent with illusory information, and 0% would mean none. Figures 3.2.3 and 3.2.4 provide data from representative trials showing whether corrective movements of the unseen hand were considered directionally consistent with the errors made by the seen hand.

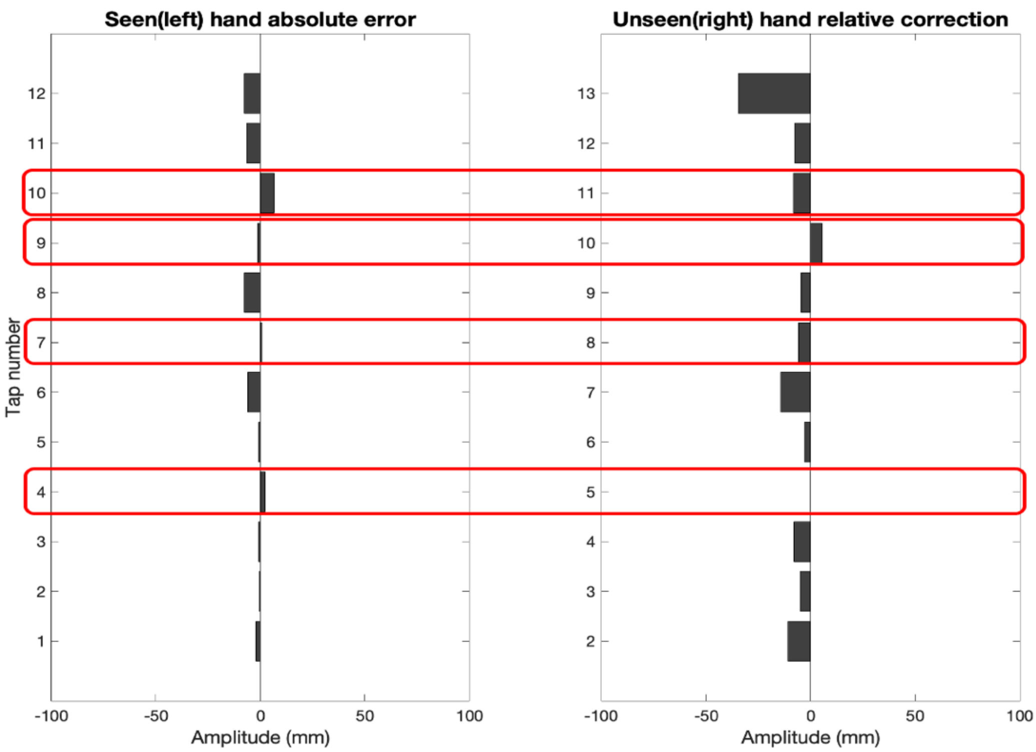


Figure 3.2.3 The two horizontal bar charts represent how we defined the corrective movement in the azimuthal direction in a trial. The data is from a representative trial in one of the left mirror conditions. The bar chart on the left side shows the seen hand's absolute error in the azimuthal direction, and the right bar chart shows the unseen hand's relative correction in the azimuthal direction. The error of the seen hand was calculated by finding the absolute distance on the frontal plane between the seen hand's far target tap position and the seen hand's far target coordinate. The correction of the unseen hand was calculated by finding the relative distance on the frontal plane between the unseen hand tap position (when recognising the seen hand error) and the following unseen hand tap position. If the direction of the seen hand error and that of the unseen hand is the same, it is assumed that the unseen hand made a correction according to the direction on the mirror. On the other hand, if it headed in the opposite direction, it is assumed that the unseen hand did not follow the illusion. The above bar chart compares 12 seen hand errors and unseen hand corrections. Taps that are highlighted in a red box are headed to the opposite direction of the given visual information. Therefore, this representative trial shows four failures (seen hand's tap numbers 4, 7, 9, and 10) in azimuth correction to the illusive image out of 12 taps.

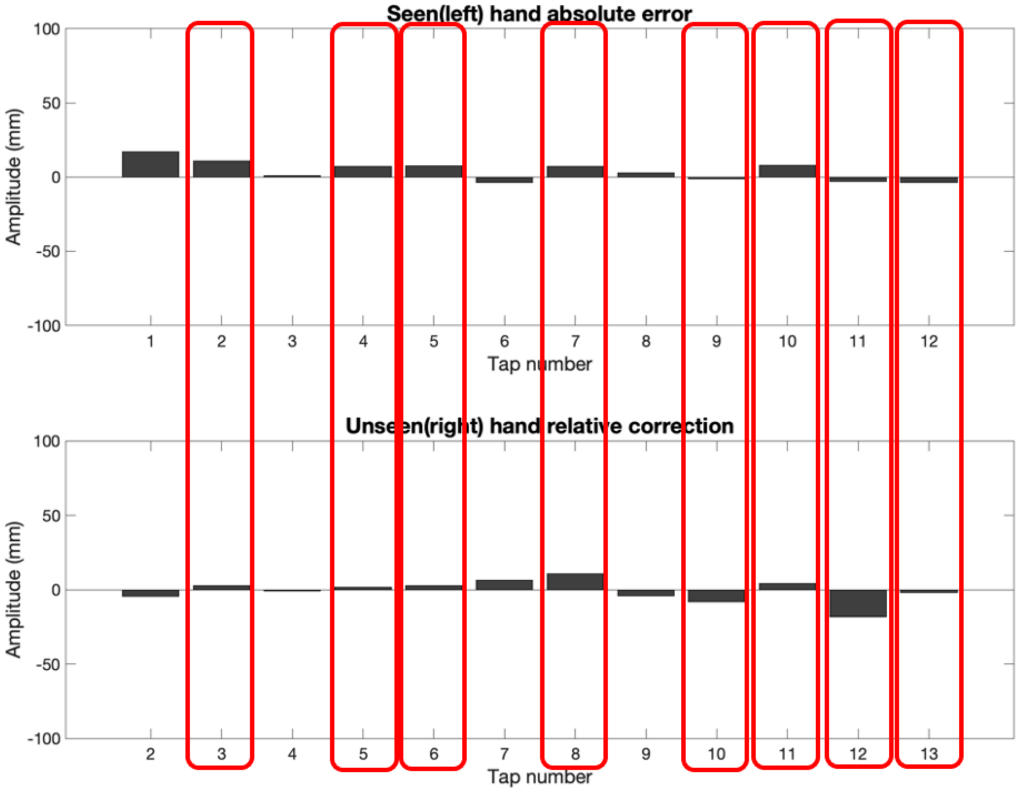


Figure 3.2.4 The two vertical bar charts represent how we defined the corrective movement in the radial direction in a trial. The data of this figure uses the same representative trial data of the left mirror condition in Figure 3.2.2. The above bar chart shows the seen hand's absolute error in the radial direction, and the below bar chart shows the unseen hand's relative correction in the radial direction. The seen hand error was calculated by finding the absolute distance on the sagittal plane between the seen hand's far target tap position and the actual seen hand far target coordinate. The correction of the unseen hand was calculated by finding the relative distance on the sagittal plane between the unseen hand tap position (when recognising the seen hand error) and the subsequent unseen hand tap position. If the direction of the seen hand error and that of the unseen hand is the opposite, it is assumed that the unseen hand made a correction following the direction in the mirror. On the other hand, if the unseen hand headed to the same direction, it is assumed that it did not follow the illusion. The above bar chart compares 12 seen hand errors and unseen hand corrections. Taps that are highlighted in a red box are headed to the same direction as the given visual information. Therefore, this representative trial shows eight failures (seen hand's tap numbers 2,4,5,7,9,10,11 and 12) of radial correction to the illusive image out of 12 taps.

Statistical analysis

Data were analysed by using SPSS (IBM SPSS Statistics, Version 27.0. Armonk, NY, USA) and all normality checks were conducted. The data were normally distributed and appropriate for analysis using parametric tests. Individual mean values for the factors of interest were calculated after trial mean values were calculated. The *directional correction rate* was analysed via a 2 × 2 × 2 (*Head side* [left, right] × *Mirror* [mirror, opaque screen] × *Direction* [azimuthal, radial]) analysis of variance (ANOVA) with repeated measures. The interactions between simple effects were analysed with multiple comparison subject to Bonferroni correction. The threshold for statistical significance was set to $p < 0.05$.

Section 2 Results

Directional correction rate

Across the experiment, the mean directional correction rate was higher when the mirror was in place (mean = 85.05 $\pm$ 3.74 %) than when replaced by an opaque screen (mean = 77.6 $\pm$ 4.15 %), leading to a significant main effect of *Mirror*, $F(1,19) = 139.74$, $p < 0.001$, $\eta_p^2 = 0.880$. However, *Mirror* x *Direction*, $F(1,19) = 29.05$, $p < 0.001$, $\eta_p^2 = 0.605$ interaction suggested a more complex relationship between factors. The results of the complex interaction are shown in Figure 3.2.5. When the opaque screen was in place, the correction rate in the radial direction was higher than in the azimuthal direction, *Vision*, $F(1,19) = 6.39$, $p = 0.021$, $\eta_p^2 = 0.252$. However, when the mirror is in place, the correction rate in the azimuthal direction became higher than in the radial direction, *Mirror*, $F(1,19) = 19.762$, $p < 0.001$, $\eta_p^2 = 0.510$.

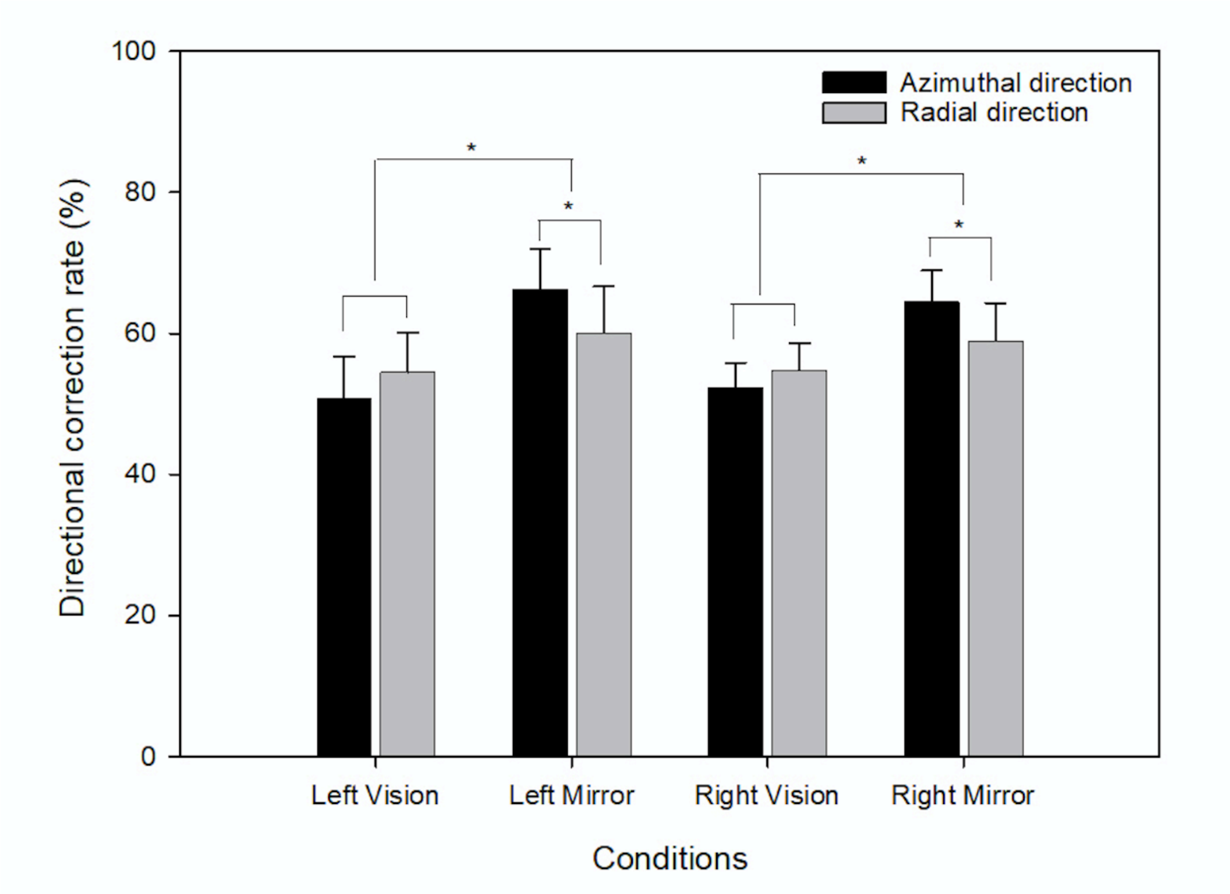


Figure 3.2.5 Mean directional correction rate for the four conditions. Error bars denote standard error, and asterisks denote statistical significance. This bar chart shows the correction rate of the azimuthal and radial direction in each condition. The correction rate is the calculated percentage of how many corrective taps occurred in the total taps of all participants in every trial. Overall, the mirror condition showed a higher correction rate than the vision condition. The presence of a mirror increased the correction rate in the azimuthal direction than in the radial direction.

	Left Vision	Left Mirror	Right Vision	Right Mirror
Azimuthal direction	50.73 (6.04)	66.25 (5.75)	52.35 (3.50)	64.51 (4.44)
Radial direction	54.49 (5.56)	60.07 (6.57)	54.80 (3.80)	58.95 (5.39)

Table 3.2.1 Mean (and standard error) values of directional correction rate.

Section 2 Discussion

The directional correction rate was examined in order to identify whether the unseen hand produced corrective movements that were directionally consistent with responding to the mirror visual feedback. The result of this analysis reveals that the unseen hand's consistency was higher in the mirror conditions than the opaque screen conditions, suggesting that to some extent at least, the mirror visual feedback influenced the movements of the unseen hand as anticipated.

An intriguing finding from the mirror condition was that the azimuthal correction rate was much greater than the radial correction rate. This differs from the vision conditions, where the correction rates in both directions were comparable. Comparison of correction rates in two different directions may relate to the study of the precision of visual and proprioceptive localisation through aiming tasks. It has been demonstrated that vision may contribute more to aiming precision in the azimuthal direction, whereas proprioception appears to be more concerned with precision in the radial direction (Van Beers et al., 1998). In present experiment, the increase in azimuthal correction caused by mirror visual feedback appears to be attributable to the effect that visual information had on precise aiming. The known influence of visual capture in controlling movements under mirror feedback conditions likely accounts for this (Holmes et al., 2004).

However, the high correction rates in the vision (opaque screen) conditions strongly suggest that correction rates do not precisely identify illusory-driven corrective movements. Given that the large amounts of positional drift observed across complete trials is the result of the accumulation of multiple small corrective movements, only considering the direction of such movements appears to be a rather crude method of examining the relationship between the limbs. While the direction is crucial in the spatial characteristics of aiming errors, one of the most key attributes to consider is the extent of the error. The extent of the correction in the aiming task is determined by how far away the error is; if the error size appears small, it may not be perceived. The aiming variability is consistently observed in aiming performance for the same reason. Exploration of correction that does not consider the extent, therefore, inevitably may reveal flaws. As shown in Figures 3.2.3 and 3.2.4, Many of the measures taken were very small and may have been the result of variable error rather than any particular correction; again, this appears to weaken the analytical approach.

Even though it was an investigation of a correction rate that did not take into account the extent, it is noteworthy that the rate exceeded 50% in the vision condition. The fact that bimanual movements are more stable when both hands move in a mirror-symmetrical direction rather than parallel may explain the high correction rate of the vision condition. Given that bimanual movement is mirror symmetric, it is predictable that when one hand points outward, the other hand also turns outward (Swinnen, 2002). When one hand points inward, the movement of the other hand inward is stable bimanual movement. According to the hypothesis, if the error of the seen hand occurs to the left, we can expect the correction of the subsequent unseen hand to occur to the left. In order to accurately aim at the target, if the participant used a strategy in which both hands moved outward once and then inward in the next movement, it may have been counted as a corrective movement, which meets the hypothesis even in the vision condition.

The ultimate goal of the analysis was to identify the unseen hand's movement that did not follow the illusive information on a movement-by-movement basis. To this end, the need for advanced analysis tools, such as approaches that can specify corrections in response to illusory information and filters that control the aim point a small distance away from the target has been demonstrated. The next section will propose a novel analytical method that can specify aiming movements with corrective intention by comparing the error of the seen hand and the corrective movement of the unseen hand.

Section 3: Comparing correction angles can distinguish corrections caused by mirror illusion

Background

The previous section (Section 2) aimed to examine whether participants made movements with their unseen hand that were 'directionally corrective' based on the mirror visual feedback they received. This involved capturing the position of the seen hand for each movement to the far target (x) and then determining whether the unseen hand made a directionally corrective movement consistent with the mirror visual feedback received when making the subsequent movement (x+1). This analysis considered movements to the far target in both the azimuthal (left/right) and radial (near/far) dimensions. By simply counting the number of movements made by the unseen hand that were either directionally *consistent* or directionally *inconsistent* with mirror visual feedback, it was able to calculate the *directional correction rate*; that is, the proportion of movements where the unseen hand made a corrective movement in a direction consistent with the illusory visual feedback they received. Section 2 showed that the presence of a mirror resulted in a directional correction rate of 85.1%. The directional correction rate was calculated in the same way for the *vision* condition and was significantly lower at 77.6 %.

However, while this directional analysis provided some insight into the relationship between mirror visual feedback and motor control, the high correction rate in the *vision* condition implied limitations in identifying the relationship between seen and unseen hand in each aiming movement. An unseen limb movement considered directionally consistent could nonetheless be markedly inconsistent in terms of the magnitude of the correction.

Comparing the correction angle formed when the hand moves back to the near target and then heads to the far target may further investigate the relationship between the error produced by the seen hand and the subsequent corrective movements made by the unseen hand. Such an approach should provide a means of incorporating both the direction and *extent* of the unseen limb's corrective movement.

Utilising correction angles is supported by the work of Sober and Sabes (2003). They explored motor planning when discrepancies exist between visual target location and actual hand position. Two phases of motor planning were considered when estimating goal-directed movement. One was movement vector planning which represents the planned movement kinematics, and the other was limb dynamics which represents transforming a plan into a joint-based motor command. Movement vector planning estimates the direction to go when reaching and was found to be heavily dependent on visual information. Since mirror visual feedback increases dominance for visual information rather than proprioception, the correction angle is expected to play a similar role as a movement vector that observes the direction of the aiming movement.

The correction angle suggested here as an analysis approach may also be found in visuomotor adaptation research. Peled and Karniel (2012) used the angle as both a dependent and independent variable in their research on visuomotor rotation adaptation. In their study, participants were instructed to look at a computer screen while sitting on a chair. A moving pointer on the screen indicated the operation of the robotic arm, and a target to aim was displayed on the screen along with the start signal. During the experiment, the movement of the hand cursor was angularly rotated without the participant's awareness by manipulating the movement of the robotic arm from the starting point. They collected the corrective movement of the participants as an angle at the starting point and observed adaptation through repeated trials. Although their experiment differs from ours in terms of experimental setting and purpose, it is noteworthy that the angle at the starting point was utilised to examine participants' aiming corrective movement based on a captured error by the vision. In light of this, the present experiment can benefit greatly from the strategy of predicting, observing, and comparing the movement of the unseen hand by finding the angle.

Figure 3.3.1 provides an illustration of how one may analyse correction angles to better understand the motor behaviour observed. The seen hand error is observed as mirror visual feedback that allows the determination of a *predicted correction angle* (PCA) based on the angular adjustment required by the unseen hand to *correct* for this error as it moves back to the near target and then away to the far target. This angle may then be compared with the *actual correction angle* (ACA) created by the unseen hand's movement.

The main goal of this section was to describe the relationship between PCA and ACA, and explore the differences between these angles when movements were made with and without mirror visual feedback.

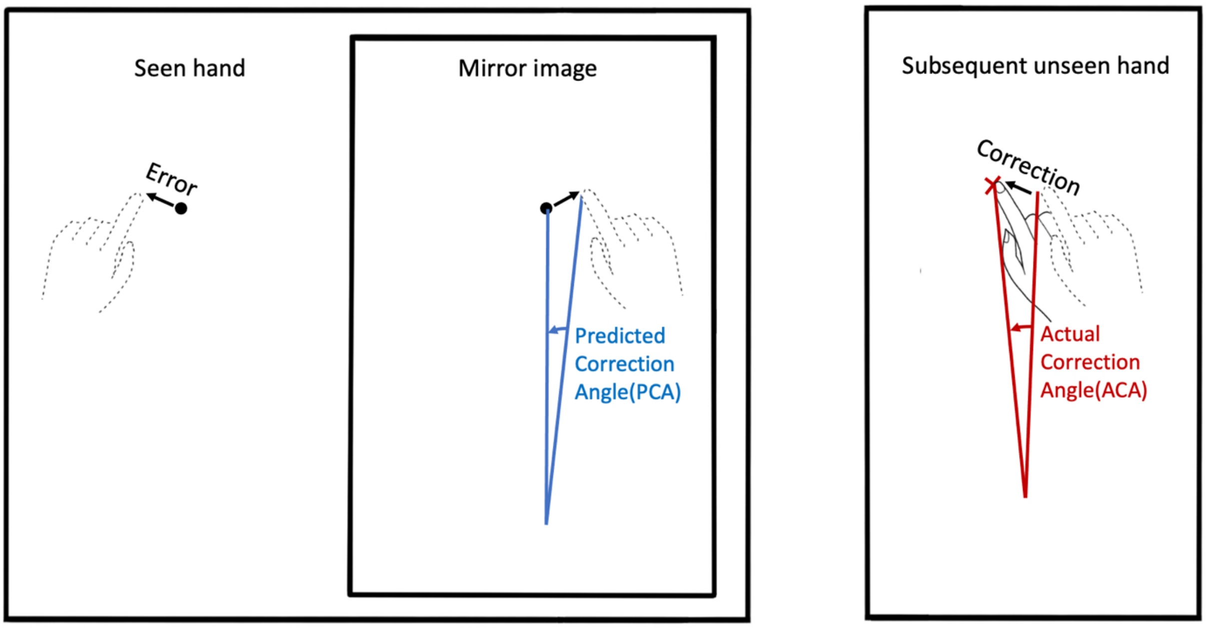


Figure 3.3.1 A schematic illustration of the predicted correction angle and actual correction angle of the unseen hand. This figure shows one corrective movement from the representative trial in the left mirror condition. The rotated angle suggested by the seen hand error can become an indicator to predict the unseen hand's correction angle in the following tap. The trajectory of the seen hand is flipped mirror symmetrically, then moved to the unseen hand area to realise the image on the mirror. The blue line represents the predicted trajectory of the hand in the mirror, and the red line represents the actual trajectory of the unseen hand. The predicted correction angle of the unseen hand (PCA) is created by connecting the line from the illusive hand's far target tap position, near target coordinate, and ending at the far target coordinate (blue line). The actual correction angle of the unseen hand (ACA) is created by connecting the line from the unseen hand's far target tap position, near target tap position, and ending at the subsequent far target tap position (red line). By matching PCA and ACA, how well the unseen hand follows the reflected image of the seen hand can be predicted.

Data analysis

The main variables of interest were the unseen hand's *predicted correction angle (PCA)* and *actual correction angle (ACA)*.

Correlation between predicted correction angle (PCA) and actual correction angle (ACA) - For each movement in each trial and for all participants, the PCA was calculated (based on the coordinates of the seen limb) and ACA (based on the coordinates of the unseen limb) were analysed via a correlation coefficient. For the PCA, coordinates from the seen hand area were used. (See Figure 3.3.1 and 3.3.2 for more details)

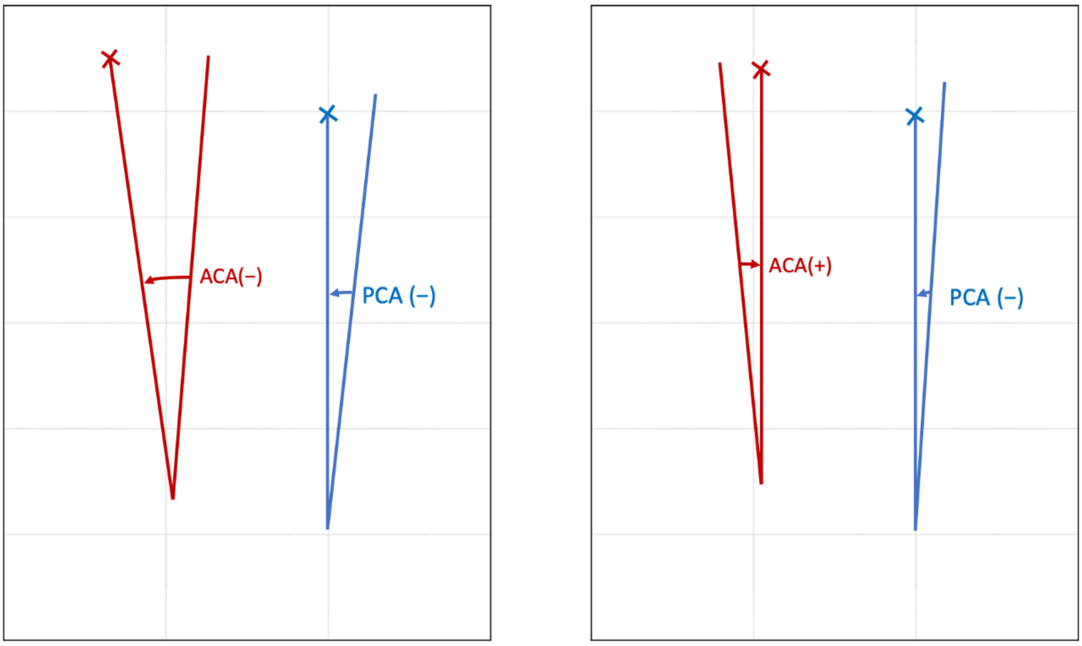
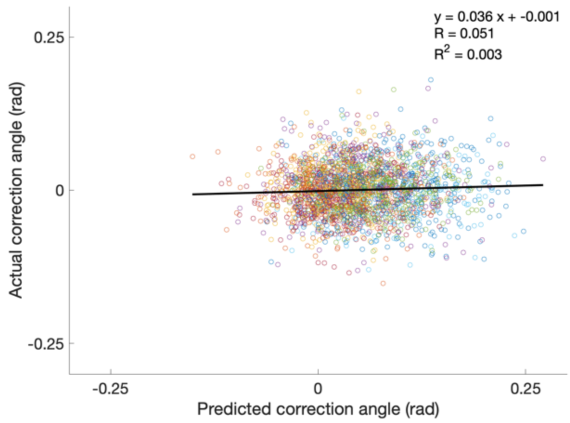


Figure 3.3.2 An illustration of how directional components are applied in PCA and ACA. This figure shows two corrective attempts in the left mirror condition. The blue lines represent the PCA trajectory from the illusive image, and the red lines represent the ACA trajectory from the unseen hand. The cross mark in the blue line shows the far target position in the mirror. The cross mark in the red line shows the corrected far target tap position of the subsequent unseen hand. A negative value was applied to the angles when the angle heads to the left, and a positive value was applied if it heads to the right.

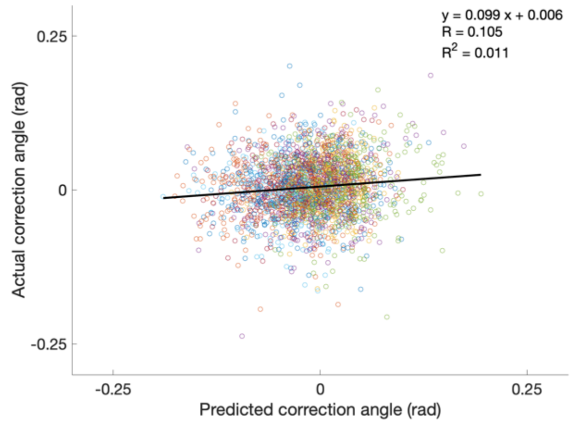
Section 3 Results

Coefficient correlation between predicted correction angle (PCA)(x) and actual correction angle (ACA)(x+1)

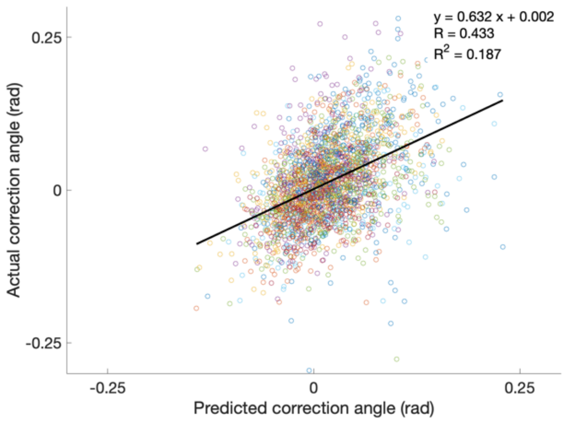
A correlation coefficient was computed to assess the relationship between the PCA and the unseen hand's ACA in Figure 3.3.3. There was a moderate positive correlation between the two variables in mirror conditions, *Left mirror*, $r= 0.433$, $r^2 = 0.187$, $p < 0.001$, *Right mirror*, $r=0.422$, $r^2 = 0.178$, $p < 0.001$. However, PCA did not appear to be associated with the ACA in vision conditions, *Left vision*, r = 0.051, $r^2 = 0.003$, p = 0.012, *Right vision*, r=0.105, $r^2 = 0.011$, $p < 0.001$.



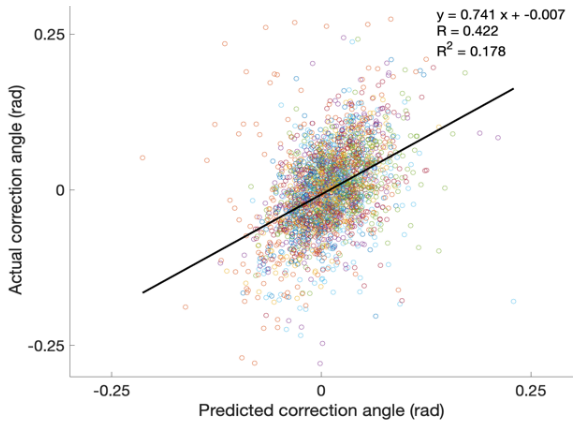
3.3.3-a Left Vision



3.3.3-c Right Vision



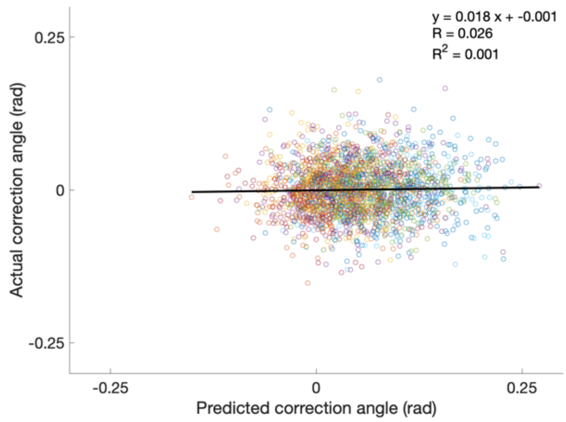
3.3.3-b Left Mirror



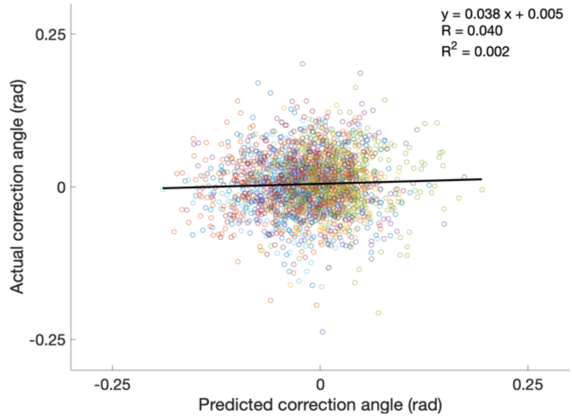
3.3.3-d Right Mirror

Figure 3.3.3 Correlation coefficient between PCA(x) and ACA(x+1) for the four conditions in scatter plot.

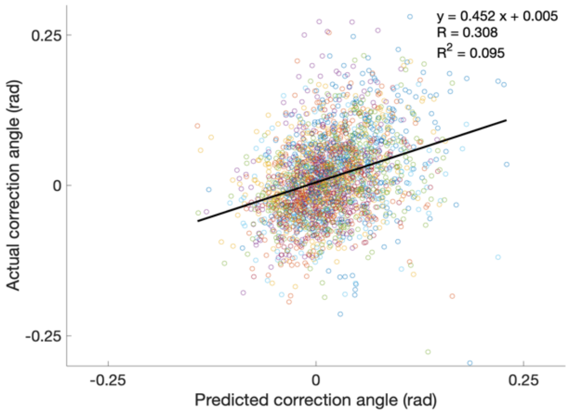
The analysis of this section was performed under the hypothesis that positional drift is caused by the accumulation of subsequent unseen hand corrections based on seen hand errors. To clarify why the error of the seen hand is compared to the subsequent unseen hand aimed position, the unseen hand's ACA that occurred at the same time as the seen hand's PCA (x, x), the ACA that occurred after the seen hand's PCA (x, x+1), and the second ACA after the seen hand's PCA (x, x+2) were compared with the seen hand.



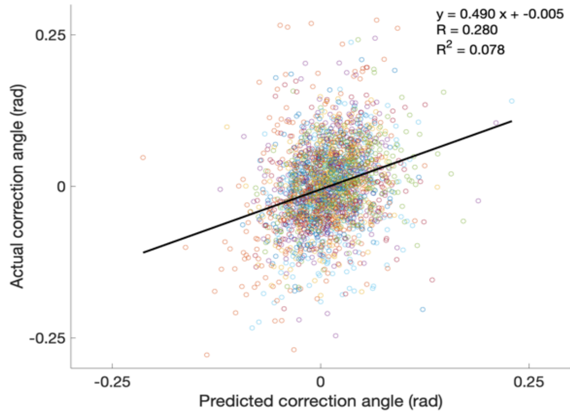
3.3.4-a Left Vision



3.3.4-c Right Vision



3.3.4-b Left Mirror



3.3.4-d Right Mirror

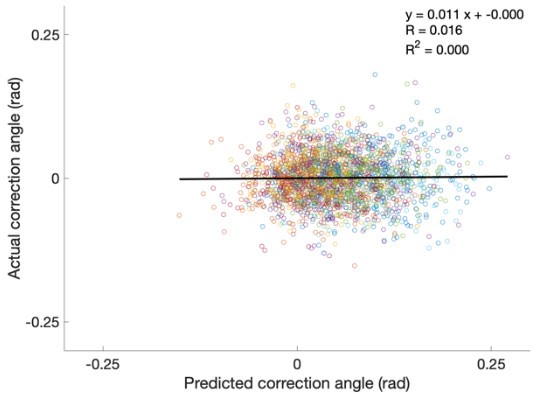
Figure 3.3.4 Correlation coefficient between PCA(x) and ACA(x) for the four conditions in scatter plot.

Coefficient correlation between predicted correction angle (PCA)(x) and actual correction angle (ACA)(x)

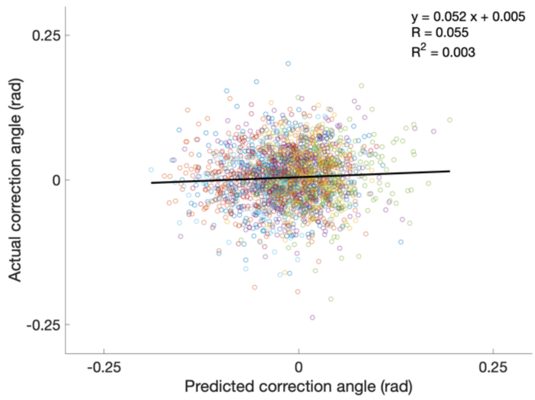
A correlation coefficient was computed to assess the relationship between the PCA(x) and the unseen hand's ACA(x) in Figure 3.3.4. There was a weak positive correlation between the two variables in mirror conditions, *Left mirror*, r= 0.308, $r^2 = 0.095$, $p < 0.001$, *Right mirror*, r=0.280, $r^2 = 0.078$, $p < 0.001$. However, PCA did not appear to be associated with the ACA in vision conditions, *Left vision*, r = 0.026, $r^2 = 0.001$, p = 0.202, *Right vision*, r=0.040, $r^2 = 0.002$, p = 0.048.

Coefficient correlation between predicted correction angle (PCA)(x) and actual correction angle (ACA)(x+2)

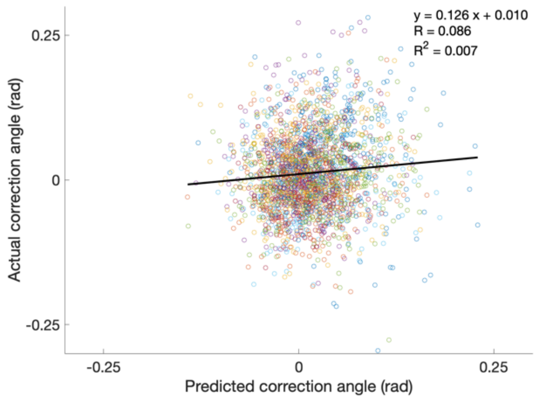
A correlation coefficient was computed to assess the relationship between the PCA(x) and the unseen hand's ACA(x+2) in Figure 3.3.5. PCA did not appear to be associated with the ACA in all conditions: Left vision ($r=0.016$, $r^2 < 0.001$, $p = 0.437$), Left mirror ($r= 0.086$, $r^2 = 0.007$, $p < 0.001$), Right vision ($r=0.055$, $r^2 = 0.003$, $p = 0.007$), Right mirror ($r=-0.030$, $r^2 = 0.001$, $p = 0.148$).



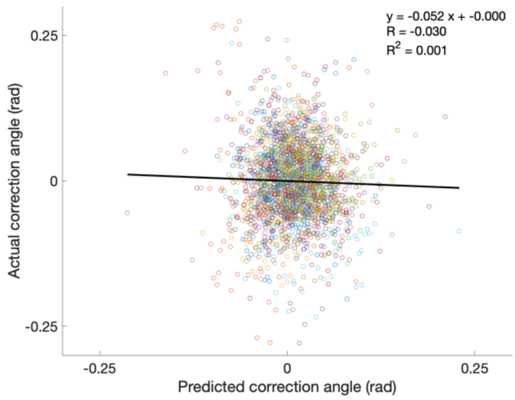
3.3.5-a Left Vision



3.3.5-c Right Vision



3.3.5-b Left Mirror



3.3.5-d Right Mirror

Figure 3.3.5 Correlation coefficient between PCA(x) and ACA(x+2) for the four conditions in scatter plot.

Section 3 Discussion

This section compared the seen hand's error and the unseen hand's correction with the rotated angle (far target – near target – far target), or correction angle to overcome the limitation of directional analysis at the far target. Correction angle at the near target was suggested as a method that can cover both the direction and distance of the corrective movement in the far target. We found a correlation by comparing the PCA and the ACA. The highest correlation rate was observed when comparing the seen hand's PCA and the subsequent unseen hand's ACA in the correction of each movement.

By comparing PCA and ACA, we were able to compare the unseen hand's relative correction according to the seen hand's absolute error. Comparing the two angles showed a bigger positive correlation rate in the mirror condition over the vision condition. In all vision conditions, the correlation rate showed an average close to 0, indicating that PCA has a very low correlation to the ACA. The comparison of correction angles captures the characteristics of bimanual movement in the mirror condition, which explains the difference between the correlation of the mirror condition and the vision condition. PCA was collected after the coordination of the seen hand's movement was flipped mirror-symmetrically. The flipped hand movement expresses the movement of the illusive hand on the mirror, where the participant believes it as the visual information that it is his own unseen hand during the trial. The difference between the target in the mirror and the relative position of the illusive hand provided the information that can predict the actual unseen hand's reaching movement plan. In the meantime, ACA was obtained with the relative position of two consecutive actual unseen hand taps. PCA and ACA, well-fitted to the characteristics of the mirror visual feedback, must have contributed to creating a clear correlation rate in the mirror condition and the vision condition.

The correction angle made it possible to explore which correction of the unseen hand should be compared with the seen hand's error. Up to this point, we explored correction based on the hypothesis that the drift of the unseen hand occurred due to the accumulation of the subsequent unseen hand correction according to the seen hand's error.

As a novel tool (correction angles) that includes an extent and a directional component of movement is developed, simply checking which of the unseen hand's movements is the most appropriate to compare with the seen hand's given error was done. Following are the observed taps: the unseen hand's correction simultaneous to the seen hand's error(x), the correction of the unseen hand after the seen hand's error(x+1), and the second correction after the seen hand's error(x+2). As a result, among the options of the unseen hand, the highest correlation rate was found in the subsequent unseen hand's movement according to the seen hand's error.

The correction of the unseen hand has the highest possibility of occurrence at the aiming directly afterwards the error, neither simultaneous with the error nor second aiming movements after the error. This finding lends credence to the idea that drift is generated by the accumulation of subsequent unseen hand corrections based on the given error of the seen hand. The reason for the online correction rate being relatively lower than the subsequent correction rate can be found in the study of movement plan according to vision

(Ricker et al., 1999). The online correction that occurs during aiming movement may have been controlled by the gaze point control in our experiment. As the vision is fixed to the far target, the corrections during the reaching movement may have been suppressed. Also, it may have gone toward the target according to the correction plan set up prior to starting the aiming movement. Therefore, rather than the unseen hand's correction happening simultaneously to the seen hand's error, it seemed to have occurred in the next aiming movement.

In this section, a novel analysis was proposed using the correction angle, which includes the extent and directional component of the correction that occurred at the far target. Using this method, the movement of the unseen hand was predicted (PCA), and the predicted movement was compared with the actual unseen hand's movement (ACA). The correlation between PCA and ACA was stronger in the mirror condition than in the vision condition, indicating that the correction angle analysis could be an illusion-specific method.

However, in order to compare PCA and ACA on a movement-by-movement basis, an additional tool to distinguish between the hand pointing to the target and the hand pointing away from the target in the mirror should be provided. In the following section, tools that can distinguish between aimed points that are directed towards a target in the mirror and those that are not will be systematically investigated.

Section 4: Creating a circular threshold around the predicted target to assess whether or not the target in the mirror is targeted

Background

In the previous section (Section 3), a novel approach that further examined whether the unseen hand executed movements with the unseen hand that were consistent with illusory information was suggested. The approach measured the angles produced as the hands returned from the far target to the near target and then returned towards the far target. Movements were then examined by comparing the predicted correction angle (PCA) measured based on the error of the seen hand, and the actual correction angle (ACA), the movements performed by the unseen hand on the subsequent movement. The relationship between PCA and ACA showed the potential of specifying the movement of the unseen hand based on illusory information. However, this is merely an explanation of the relationship between the two angles and does not give any standard for analysing each movement. It appears that further classification criteria or filters are required to develop the analysis on a movement-by-movement basis.

To determine if the movements of the unseen hand are consistent with the illusory information at each movement, the size of the trajectory as well as the comparison of the correction angle must be examined. And given that all movement involves some degree of variability, the variability also must be taken into consideration in order to determine if the movement was influenced by mirror feedback.

Aiming variability is evident with repetitive aiming movements even when there are no constraints (mirror, posture, etc.). According to Sidaway et al. (1995), when healthy individuals aim at a circular target with a 1.5 cm diameter, the aimed points could be shifted by about 1 cm. The aiming variability of an unseen hand during mirror visual feedback was observed by Holmes et al. (2006). They reported the standard error of the unseen hand's mean reaching error being under 1 cm. Given the variability of movement exists, the intention of this section was to create a perimeter (range and shape) of aiming variability as a threshold, with any movements falling outside this perimeter considered to be made in a manner inconsistent with the illusory information provided by the mirror.

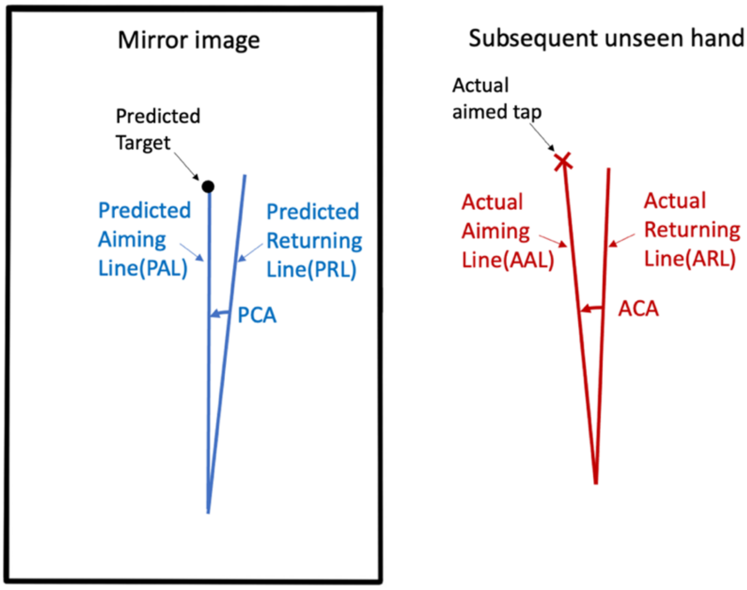


Figure 3.4.1 Lines that compose PCA and ACA. The predicted returning line (PRL) connects the illusive hand's far target aimed point(x) to the near target coordinate, and the predicted aiming line (PAL) connects the near target coordinate to the far target coordinate. The actual returning line (ARL) connects the unseen hand's far target aimed point(x) to the unseen hand's near target aimed point(x), and the Actual aiming line (AAL) connects the unseen hand's near target aimed point(x) to the unseen hand's subsequent far target aimed point(x+1). To observe the relative position between the predicted target and the actual unseen hand aimed point, line fitting is needed to match PCA and ACA.

Aiming variability was captured by gathering the position of the unseen hand relative to the predicted (far) target. Placing PCA trajectory lines over ACA trajectory lines reveals the relative position of the actual aimed position from the predicted target (see Figure 3.4.2). In proposing this form of analysis, it is important for the reader to recognise that the PCA trajectory lines are adjusted from one movement to the next based on the movement distance of the ACA, since the movement distance of the unseen hand may be (and typically was) different from the movement distance of the seen hand. In section 1, we presented the straight-line distance (movement distance) connecting hand positions when aiming towards the near and far targets; and in the mirror condition, it was confirmed that the travelled distance of the unseen hand was significantly longer than that of the seen hand.

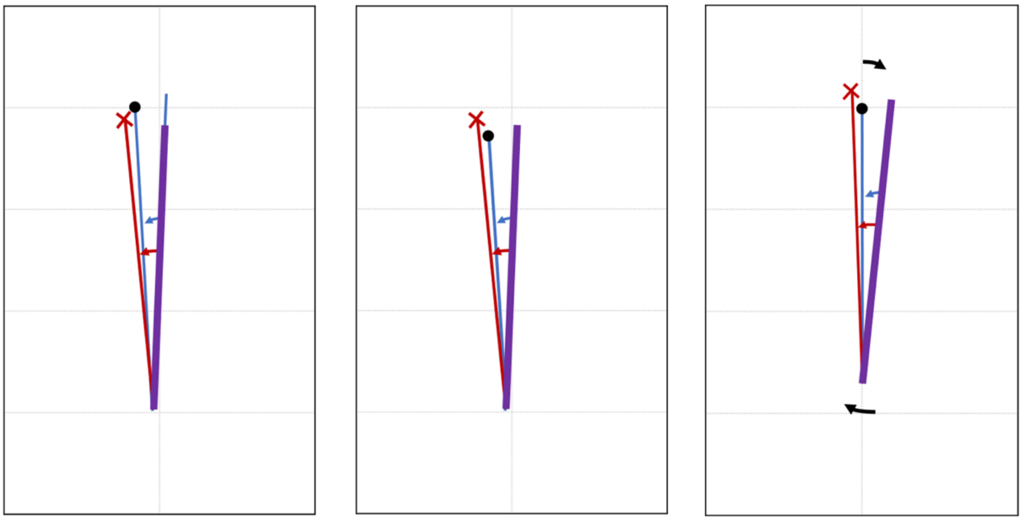


Figure 3.4.2-1
Placing PRL over ARL

Figure 3.4.2-2
PCA lines are fitted to the length of ARL

Figure 3.4.2-3
Angles are aligned by placing PAL from the predicted target at 6 o'clock position

Figure 3.4.2 Line fitting and angle alignment in steps. These steps are based on the explanation of PCA and ACA in Figure 1. First, PRL was placed over the ARL (figure 3.4.2-1). Secondly, the PCA lines (PRL, PAL) are fitted to the length of ARL (figure 3.4.2-2). Finally, matched angles are aligned by placing PAL from the predicted target at the 6 o'clock position to integrate the relative position of all unseen hand aimed points (figure 3.4.2-3).

As demonstrated already above, the substantial drift of the unseen hand observed appears to occur gradually in our study as a result of cumulative ‘corrections’. However, as a result, it is necessary to adjust the PCA based on the ARL from movement to movement in order to accurately capture behaviour in response to illusory information.

This adjustment or ‘fitting’ of the PCA's trajectory lines based on the ARL appears to offer a solution that allows the relative position of the actual movement to the target to be considered in relation to the predicted target. While the unseen hand is provided with visual information (via the mirror) particularly in relation to the far target, the role of proprioception presumably remains important in controlling movement distance for the return to the near target and the movement distance to the far target for the following movement (Patterson et al., 2017).

This section aimed to find the size and shape of the aiming variability of the unseen hand, which should be considered to determine whether the movement of the unseen hand was consistent with the illusory information on a movement-by-movement basis. Points within the aiming variability are the points aimed along the illusory information; therefore, these may be disregarded when investigating an aim that is inconsistent with the illusive information.

Data analysis

The main variable of interest was *positional drift at the predicted target*.

Positional drift at the predicted target – The furthest point from the predicted target in each trial of all participants were found and calculated the straight length to the far target (see Figure 3.4.2). Figure 3.4.3 shows each unseen hand's aimed points to the predicted target for every trial, for each condition.

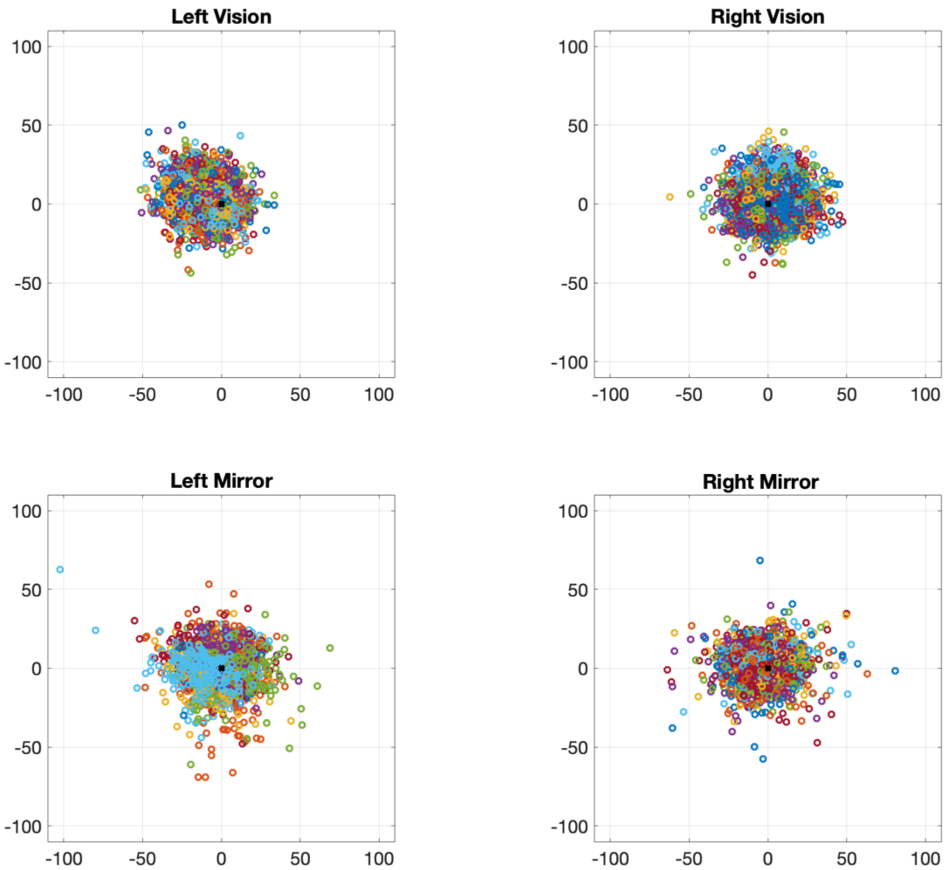


Figure 3.4.3 Actual unseen hand aimed points that headed to the predicted target for each condition. The predicted target is marked as x on position (0, 0). Every actual unseen hand aimed point from all participants is marked as small circles in relative position to the predicted target. Each participant was colour-coded. In all conditions, actual aimed points are gathered around the predicted target. However, in mirror condition, some aimed points drifted away from the predicted target. Scale values are in millimetres.

Statistical analysis

Data were analysed by using SPSS (IBM SPSS Statistics, Version 27.0. Armonk, NY, USA) and all normality checks were conducted. The data were normally distributed and appropriate for analysis using parametric tests. Individual mean values were calculated for the factors of interest. *Positional drift at the predicted target* was analysed via a 2 × 2 (*Head side* [left, right] × *Mirror* [mirror, opaque screen]) analysis of variance (ANOVA) with repeated measures. The threshold for statistical significance was set to $p < 0.05$.

Section 4 Results

Positional drift at the predicted target

Figure 3.4.4 shows the positions reached by participants when aiming to the far target for those movements that represent the furthest positional drift in relation to the predicted target for every trial; and for each condition. Figure 3.4.5 shows the related group mean values.

As can be seen, these values are comparable across all conditions (mean length = 31.19 $\pm$ 0.69mm), leading to no significant effects or interactions, *Head*, $F(1,19) = 0.442$, $p = 0.515$, $\eta_p^2 = 0.024$, *Mirror*, $F(1,19) = 0.016$, $p = 0.902$, $\eta_p^2 = 0.001$, *Head* x *Mirror* interaction, $F(1,19) = 0.2$, $p = 0.660$, $\eta_p^2 = 0.011$.

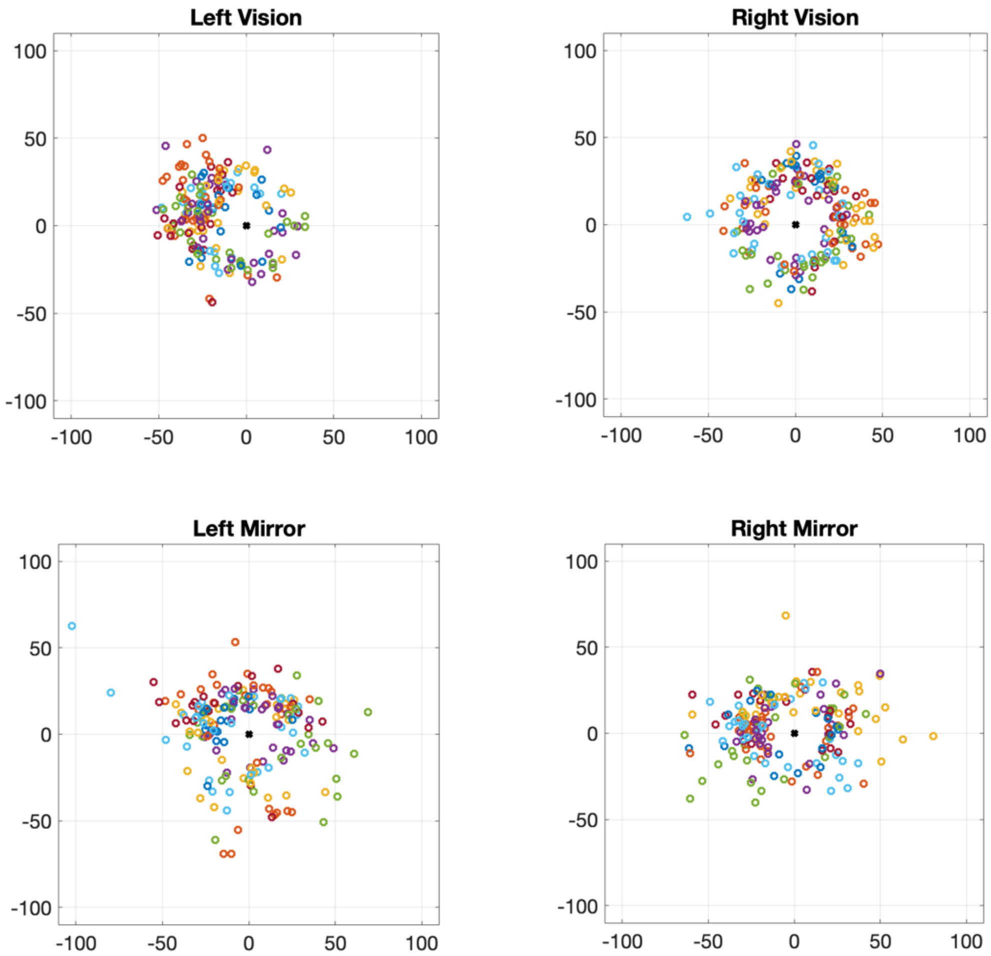


Figure 3.4.4 Positional drifts at the predicted target for each condition. The predicted target is marked as x on position (0, 0). Each participant's furthest actual aimed points from the predicted target from all trials are marked as small circles. Each participant was colour-coded. In all conditions, there is no aimed points within the 20mm radius of the predicted target. This finding suggests a circular threshold with a 20mm radius from the predicted target. Scale values are in millimetres.

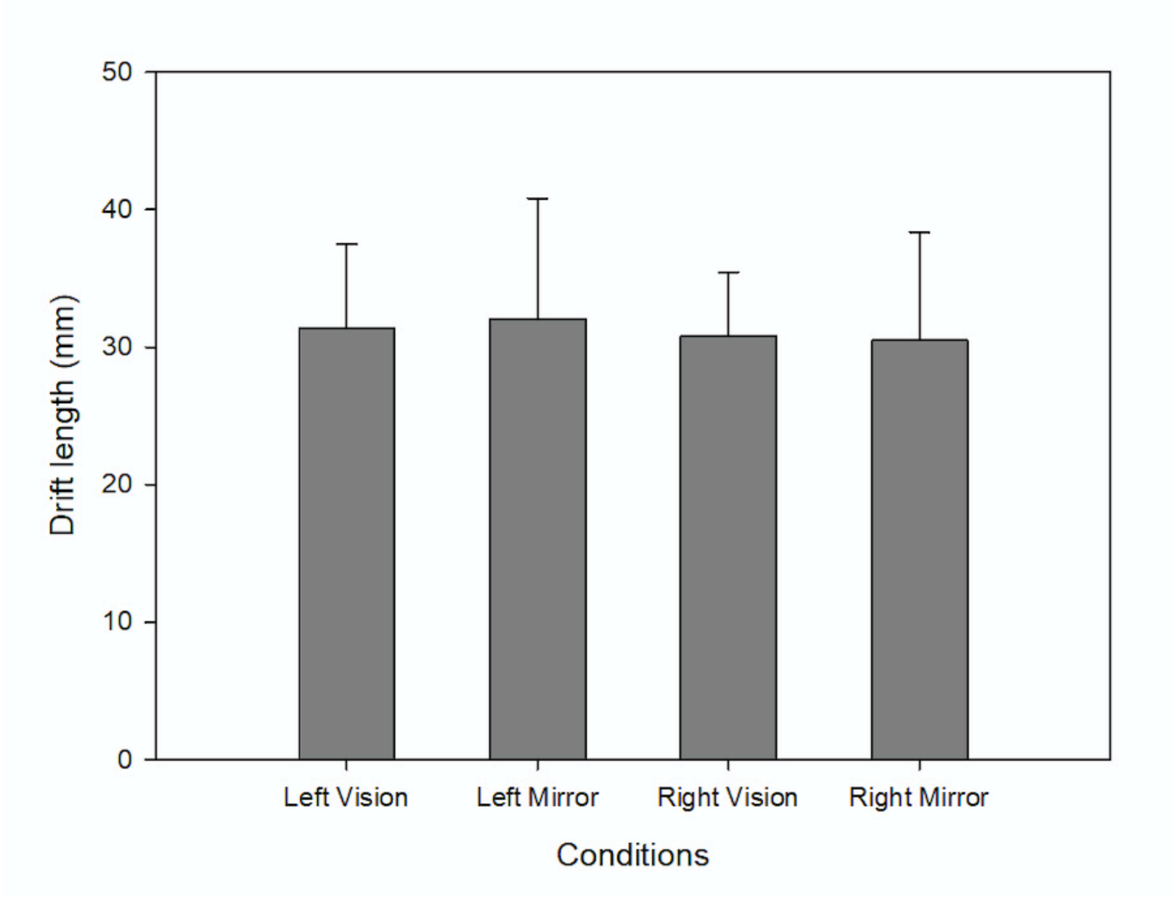


Figure 3.4.5 Mean positional drift length at the predicted target for the four conditions. Error bars denote standard error. The positional drift at the predicted target was comparable in all conditions (mean length = 31.19 ± 0.69mm), leading to no significant effects or interactions.

	Left Vision	Left Mirror	Right Vision	Right Mirror
Drift length	31.43 (6.07)	32.06 (8.76)	30.80 (4.65)	30.51 (7.87)

Table 3.4.1 Mean (and standard error) values of positional drift at the predicted target.

Section 4 Discussion

This section introduced the size and shape of the aiming variability when comparing PCA and ACA. By comparing the two angles, the relative position of all the actual aimed points were gathered in relation to the predicted target. Across all conditions, these formed a round cloud-like shape around the predicted target. A few points were scattered further in the mirror condition; however, the average size of the cluster was similar. When only the furthest taps from each trial were selected, these formed a round shape approximately 2cm away from the predicted target.

Being able to obtain these relative aimed points of all actual unseen hand aimed points from the predicted target was a significant success in this section. PCA is a correction angle that predicts the corrective movement of the subsequent unseen hand aiming position based on the reaching error of the hand in the mirror. For this PCA, the far target in the mirror is the destination point (predicted target), and for the subsequent unseen hand tap, it is a virtual target to aim for. The ACA is an angle that displays the movement of the unseen hand that follows illusory feedback. Comparing these two angles shows how the actual unseen hand's aimed points form a circle-shaped cluster around the predicted target.

The aiming variability formed with a round shape was one of the interesting findings in our experimental setting. The round shape was uncovered by leaving out only the farthest aimed points from the predicted target in each trial. The circular boundary was observed to be of similar size, regardless of the presence of mirror visual feedback. It suggests that participants would have felt that an aiming attempt moving away from the circular boundary is an aiming error. In other words, it seems that the aimed points inside the circular boundary were acceptable aiming variance for the participants.

Along with the shape of aiming variability, the size was found. A previous study reported the size of the unseen hand's aiming variability during the mirror visual feedback. Holmes and colleagues(2006) investigated the unseen hand's reaching error with a discrete reaching task, where the variability of the reaching error was approximately 1cm. Since the aiming task was repetitive, there seems to have a difference from the results of Holmes. Given that task repetition increases movement variability in terms of fatigue (Savin et al., 2021), it may also have affected aiming variability over time.

The size of the circular aiming variability was confirmed by calculating the average drift length in each condition. The farthest aimed points from the predicted target in the *mirror* condition look more scattered than in the *vision* condition. However, the average drift length, roughly 3cm, was comparable to the predicted target from each condition, and the standard deviation was less than 1cm. Hence the aimed points within the 2cm circle boundary imply that this area is where the participant felt as if he aimed at the target in the mirror.

Applying a 2cm circular threshold on the predicted target will diminish redundant effort to address the inconsistent movements to illusory information when matching PCA and ACA. Although this section explored how to apply the threshold, there is still the possibility that corrective movement can exist among the aimed points that exist outside the threshold.

Based on what we know so far, the following section will attempt to find the number of moments that did not follow illusory information during the trial.

Section 5: Identifying illusion breaks and a loss of agency over the illusory limb

Background

Based on the previous sections and related analyses, the aim was to identify where participants made movements of the unseen hand during the mirror condition that were clearly inconsistent with the illusory visual information available to them. If such movements exist, these would be indicative of an *illusion break* and a lack of agency over the illusory limb.

Three criteria were set for identifying such movements.

1. Movements must be > 50mm from the actual far target.

   Movements could only be considered if they were more than 50mm away from the actual far target. This distinguishes the mirror condition from the vision condition, leaving just the movements influenced by the mirror illusion.

2. Movements must fall outside the 'predicted' aiming arc.

   As explained in section 4, the actual movements of the unseen hand were analysed in relation to the predicted target. This involved both azimuthal and radial dimensions. For movements to be considered inconsistent with mirror-related illusory information, they must have fallen outside of the predicted aiming arc. The predicted aiming arc (range of correction angle) was drawn with two tangential lines between the circular threshold around the predicted target and the near target.

3. Movements must have been made in the opposite (azimuthal) direction to that predicted.

   Consistent with the reasons given for the analysis in Section 2, for movements to be considered inconsistent with illusory visual information, they must have deviated in the opposite direction to that predicted.

Where movements met these three criteria, it was determined that there could be confidence that movements were being made that were inconsistent with correction based on feedback from the illusory limb - and such movements would be indicative of a break in the illusion and a lack of agency over the illusory limb.

Data analysis

The main variable of interest was the *rate of illusion breaks*.

Rate of illusion breaks – Each 'corrective' movement of the unseen hand was assessed in relation to the set criteria and the proportion of movements in each trial captured for the different conditions.

Statistical analysis

Data were analysed by using SPSS (IBM SPSS Statistics, Version 27.0. Armonk, NY, USA) and all normality checks were conducted. Individual mean values were calculated for the factor of interest. The rate *of illusion breaks* was analysed via a 2 × 2 (*Head side* [left, right] × *Mirror* [mirror, opaque screen]) analysis of variance (ANOVA) with repeated measures. The threshold for statistical significance was set to $p < 0.05$.

Section 5 Results

Rate of illusion breaks

As can be seen in Figure 3.5.1, the rate of illusion breaks in mirror conditions (mean = 6.54 ± 8.67%) was significantly greater than in vision conditions, leading to a significant main effect of *Mirror,* $F(1,19) = 56.658$, $p < 0.001$, $\eta_p^2 = 0.749$.

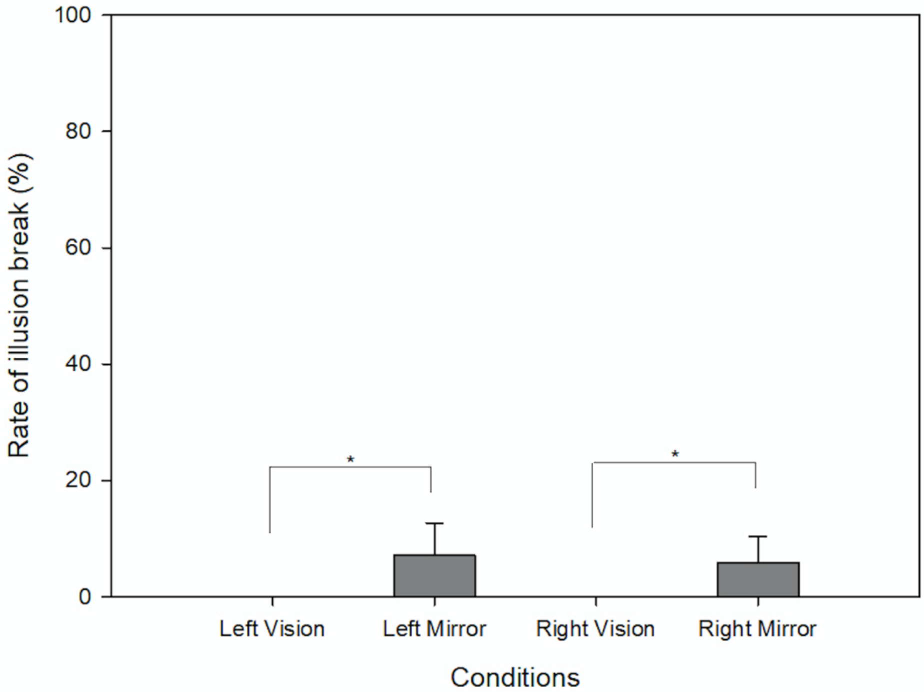


Figure 3.5.1 Mean rate of illusion breaks in each trial as a function of Head side and Mirror. Error bars denote standard error, and asterisks denote statistical significance. About 7% of all aimed points in each trial were illusion-breaking moments in mirror conditions.

	Left Vision	Left Mirror	Right Vision	Right Mirror
Rate of illusion break	0 (0)	7.16 (5.55)	0 (0)	5.93 (4.44)

Table 3.5.1 Mean (and standard error) values of rate of illusion break.

Section 5 Discussion

This section systematically observed the movement of the unseen hand according to illusive information. The illusion-inconsistent movement was tracked based on the three criteria, which was driven from previous sections. As a result, this section observed that the unseen hand's correction may not follow the illusive information at least once in a trial (15 seconds). Considering the number of aiming attempts in each trial, it seems to occur about 7% of aiming movements per trial.

This outcome brings to mind the post-experimental interview reported in Section 1. Following the mirror trial, participants mentioned the moment that their hand did not feel as controlled as they would have liked in a trial. Their comments were interpreted as a moment of doubt about the illusion and a disturbed sense of agency. The findings in this section objectively represent the perceptions of the individuals through kinematic analysis.

The findings of this section also supported the view that stated the role of explicit target. Explicit target was suggested which can increase the drift, but at the same time be a factor that breaks the illusion. The above result was obtained by comparing the position of the seen hand or unseen hand according to the position of the explicit target. Therefore, it seems self-evident to consider an explicit target as an influencing factor in illusion break.

General Discussion

The present experiment is conducted by having healthy volunteers perform symmetrical and simultaneous repetitive bimanual aiming movements with mirror visual feedback, and then investigated the unseen hand movements. Participants demonstrated positional drift of the unseen hand as with the bimanual circle drawing task (Chapter 2). While observation during these experiments suggested participants were unaware of the position drift, post-experimental interviews revealed an element of doubt regarding limb position during mirror visual feedback trials. Such doubt suggests that the participant's sense of agency over the illusory limb may be disrupted (Fink et al., 1999). As a result, this experiment aimed to explore agency over the unseen limb by looking to identify individual movements that were inconsistent with illusory information. Three criteria were set to determine for each movement whether illusory information was used to control the position of the unseen limb. Analysis suggested that the unseen hand performed at least one movement during related trials that were inconsistent with illusory visual information.

The findings presented here suggest that there were occasions when participants' agency over the illusory limb was lost, inferred because of *spatial* discrepancies between the predicted movement and the actual movement. As participants are not asked about their agency over the illusory limb and may not be aware of the movement discrepancy referred to above, this measure must be considered *implicit*. To date, studies considering agency over given movements have typically explored temporal aspects of movement (Moore, 2016), the most widely used implicit measure being intentional binding, developed by Haggard and colleagues (Haggard & Clark, 2003; Haggard et al., 2002; Haggard & Cole, 2007). Intentional binding explains the subjective shortening of time between a voluntary action and its subsequent external sensory effect (Moore & Obhi, 2012). However, there has been no research that has taken the implicit measure of a sense of agency in a spatial manner. Here, this chapter attempted to explain the alteration in the sense of agency based on the spatial manner on a movement-by-movement basis.

As noted above, disruption in the agency can be inferred when there is a mismatch between the predicted and actual position of the unseen hand. If these match, the action is likely attributed to one's self (Frith et al., 2000). On the other hand, if these do not match, the cause of the sensory stimuli may be attributed to an external source (Synofzik et al., 2008). This process of *agency registration* is usually not carried out consciously (Pacherie, 2001). However, when there is a clear discrepancy between expectations and sensory feedback, the comparator output becomes conscious, leading the subject to become aware of their motor predictions, actual movements, and sensory consequences (Slachevsky et al., 2001). This may be the case in the present study when participants made movements that were not consistent with the illusory information they received.

The degree of mismatch between the predicted and actual positions of the unseen hand may have caused a sense of agency disruption (Jeannerod (2006). To distinguish the degree of mismatch, a threshold (for aiming data) was created around the predicted target and an aiming arc was introduced (Sections 4 and 5). In the present study, the positional discrepancy of any given individual movement tended to be small – and this may have allowed the maintenance of agency – even though the location of the unseen hand sometimes shifted substantially from the initial position within a trial (drift).

The spatially implemented comparator model explains the sense of agency by indicating how accurately the unseen hand hit the target shown in the mirror. However, this alone cannot fully clarify the sense of agency experienced with mirror visual feedback. An example would be the unseen hand's proprioceptive drift in response to mirror visual feedback.
Proprioceptive drift occurs when the location of a body part shifts perceptually from proprioception to visual feedback (Tsakiris & Haggard, 2005). This may diminish the unseen hand's accuracy during mirror visual feedback (Tajima et al., 2015), and the proposed comparator model can ignore it simply because it is too far away from the target.
This is consistent with Synofzik et al. (2008)'s argument that explaining the sense of agency solely through the comparator model has limitations. They explained that multiple sensory feedback modalities, as well as a comparator model, should be considered for the explanation of a sense of agency in the case of an experiment in which the role of vision and proprioception are emphasised (Synofzik et al., 2006).
The directional component is best recognised for distinguishing between the role of vision and proprioception in mirror visual feedback (Snijders et al., 2007). Since illusory visual information has a higher influence on the left-right directional decision, we included a directional component in the classification as well as a simple mismatch to explain the sense of agency in mirror visual feedback.

Although not examined formally, it was observed that positional drift of the unseen limb increased towards the end of trials. Figure 3.2.3 demonstrates a typical trial, demonstrating how the degree of the unseen hand's correction increases near the end of the trial. Trials of the repetitive aiming task during the study commenced without any prior adaptation period for the mirror image. However, it may be that adaptation occurred during the first few seconds of mirror trials. According to Holmes and Spence (2005), the longer the exposure to the mirror-reflected hand, the more weighted movements are on visual information rather than proprioceptive information. Their result explains that the sense of ownership and agency in the mirror condition is enhanced over time. As a result, some studies have advised having an adaptation period of 6 seconds prior to any movements beginning (Holmes et al., 2004; Tajima et al., 2015). The 15-second trials performed in this study perhaps allowed the sense of agency to build and develop prior to any subsequent moments where this was then lost. Examining movements across much longer periods of time (as might be encouraged in mirror therapy) may be illuminating with regard to how the sense of agency over the illusory limb is modulated.

While the aimed points that did not follow the illusory information were classified, it is difficult to be fully confident that all other aimed points moved in accordance with the illusion. By the same argument, there remains uncertainty whether the analysis captured all moments where the agency was classified as being lost (illusion break). Nevertheless, the sophisticated analysis employed here expands the possibilities for future mirror visual feedback studies using either the same or similar approaches to implicitly measure the sense of agency. Since the properties of the unseen hand discovered during mirror visual feedback were designed for step-by-step analysis, the approach could be easily adapted for other movements/activities. Whether the approach will have the same utility with regard to examining movements in stroke patients during mirror visual feedback remains to be determined. Motor impairment that exists across hemiparetic stroke patients is likely to add complexity to the process, and the substantial variability of impairment across patients may make generalisation difficult. This will be investigated further in the following chapter 4.

Another intriguing question raised by this experiment was what other factors threaten the sense of ownership/agency during mirror visual feedback. Maintaining a sense of agency over the illusory limb could be an important factor in determining the effectiveness of mirror therapy. In contrast, not attributing limb movements in the mirror to the unseen limb may reduce the therapeutic effect. If elements that break the illusion or hinder the sense of agency are removed, a more optimal effect of mirror therapy can be expected. For example, including explicit targets (or objects) provides the participant/patient with more defined visual information that will automatically be observed in relation to their movements. This introduces the possibility for the participant/patient to observe greater error which in turn may threaten the sense of agency over the illusory limb. Controlling these issues in the environment may be of particular importance. Evidence from a meta-analysis of clinical trials involving mirror therapy for hemiparetic stroke strongly suggests that maintaining a simple environment (e.g. not including objects) is associated with a more effective intervention (Morkisch et al., 2019). How one optimises the environment to optimise the illusory experience will be returned to in Chapter 5.

In summary, this chapter showed positional drift caused by the correction of the unseen hand based on illusory information derived from the seen hand. Based on the relationship between both hands, a novel analysis is developed to predict the movement of the unseen hand. The analysis revealed that the unseen hand did not follow the illusory information at least once during the 15-second trial, which was interpreted as a moment of illusion break and a diminished sense of agency over the illusory limb.

Chapter 4. (Mirror-induced) motor extinction of the unseen impaired limb during mirror therapy in patients with left hemiparesis

Abstract

Mirror therapy has been shown to be an effective intervention for improving motor function in patients following hemiparetic stroke. While the mechanism that explains this effectiveness is uncertain, the field is also complicated by the different ways the intervention is delivered. For example, while patients typically move the *seen* hand while performing mirror therapy, whether movement of the *unseen* hand is encouraged/instructed remains unclear. Where *bimanual* movements are made, performance of the limbs and in particular the unseen (hemiparetic) limb during mirror therapy may offer clues to its effectiveness, but to date, movements performed during mirror therapy have not been examined. This study addresses the issue directly, investigating bimanual coordination in three stroke patients during mirror visual feedback, providing preliminary and exploratory data relating to the immediate impact of the intervention on movement.

Three left hemiparetic stroke patients performed 15 s trials of self-paced repetitive aiming movements (between far and near targets) with a mirror/symmetrical coordination pattern. For the *mirror* condition, the vision was directed towards the far target in the mirror. In the *vision* condition, the direction of vision was unchanged, but the mirror was replaced with an opaque screen. The movements of both hands were recorded using motion capture apparatus.

Consistent with previously reported similar studies of unimpaired participants (Chapters 2 and 3), patients demonstrated substantial positional drift of the unseen hand over the course of a 15-second trial during the mirror conditions. However, when the impaired limb was the unseen limb, related movements became hypometric in the *mirror* condition compared with the *vision* condition, a problem referred to as *motor extinction*. This may occur as a result of reduced attention to the movement of the impaired limb (and related proprioceptive signals) elicited by vision of the illusory limb in the mirror. One of the three patients studied also has spatial neglect. When the unseen hand was the impaired hand, the impact of the mirror on motor control was far more pronounced, possibly eliciting a lack of awareness of the impaired limb. The implications of the preliminary findings are discussed.

Introduction

For the rehabilitation of the hemiparetic limb following stroke, mirror therapy has been suggested as a promising intervention (Altschuler et al., 1999). A recent Cochrane review examined more than a decade of clinical research, discovering that mirror therapy accelerates functional recovery after stroke (Thieme et al., 2018). Mirror therapy for the impaired upper limb following stroke has been shown to be effective in both acute and chronic conditions (Perez-Cruzado et al., 2017). Excluding trials in which any type of stimulation (e.g. functional electrical stimulation, transcranial magnetic stimulation) was combined with mirror therapy (Cha, 2015; Schick et al., 2017), about 30 clinical trials have shown that mirror therapy improves motor function and motor impairment in stroke survivors (Morkisch et al., 2019). However, the mechanism by which mirror therapy affects the motor function of the affected limb of a stroke remains unknown (Thieme et al., 2018). Further, mirror therapy has been applied using multiple different protocols and the variability in mirror therapy protocols has broadened the scope of the intervention, creating uncertainty regarding the optimal approach. (Thieme et al., 2012; Thieme et al., 2018).

The various protocols for mirror therapy reported following stroke are carried out while adhering to some underlying and unchanging procedures and concepts. For example, patients are instructed to gaze at the reflection of their unimpaired limb in a mirror placed in their mid-saggital plane while placing the paretic limb behind the mirror; their non-paretic side in front of it. The mirror obscures the paretic side from view and directs attention to the reflection of the unimpaired limb that appears in a congruent position with the impaired (unseen) limb (Rothgangel & Braun, 2013). When the unimpaired limb is moved, patients observe the same movement in the mirror reflection appearing spatially consistent with that of their paretic limb. This typically creates a powerful illusion of the paretic limb moving, a feature of mirror therapy that is considered important (McCabe, 2011).

Protocol differences across studies may be characterised by a number of parameters; and Morkisch et al. (2019) performed a meta-analysis examining the impact some of these appear to have on the effectiveness of the intervention for hemiparesis following stroke. They considered three different parameters. A comparison of mirror sizes revealed that large mirrors were more effective than small mirrors. In terms of whether the directed movement was to be executed unimanually or bimanually, unimanual movement execution (i.e. not moving the impaired limb) delivered better results. And making movements in the absence of objects (as opposed to with them) also produced more optimal outcomes.

Perhaps most intriguing of these three findings was the superior outcomes relating to unimanual rather than bimanual movements; not only because the approach contradicts the original procedure (Altschuler et al., 1999) but also because the unimanual approach is performed in the absence of the very movement mirror therapy is aiming to improve (i.e. movement of the hemiparetic limb). To be clear, when instructed to perform unimanual execution, only the non-paretic hand in front of the mirror performs the tasks, while the paretic hand behind the mirror remains still (Arya et al., 2017; Geller et al., 2016). In contrast, for the bimanual execution approach, the participant is generally instructed to move both hands symmetrically and simultaneously while looking in the mirror (Yavuzer et al., 2008). When bimanual execution is directed, the participant is advised to move the affected limb behind the mirror "as well as possible", an approach that is consistent with the initial protocol proposed by Altschuler and colleagues(1999) (Dohle et al., 2009; Michielsen et al., 2011; Mirela Cristina et al., 2015).

The justification for unimanual movement execution appears strategic, the motor function of the affected limb being taken into account; however, while protocol changes are made, authors typically do not provide a rationale for the specific approach taken. Arya et al. (2017) instructed unimanual task-based movements with an object (e.g. lifting a glass, turning a wooden block, lifting a peg, wiping), which would have been difficult actions to accomplish with the affected hand given the participants' motor impairment levels. Similarly, Colomer et al. (2016) directed unimanual simple joint movements, but the chronic stroke survivors who participated had severe impairment (Fugl-Meyer Assessment <19), so even completing this simple task would have been difficult. Given the difficulties that many stroke survivors may have moving their hemiparetic limb, it is perhaps not surprising that unimanual movements are sometimes advised.

As the aim of mirror therapy for stroke survivors is to improve movement in their hemiparetic limb, it remains surprising that performing the intervention without attempting to move the hemiparetic limb is advised. Furthermore, performing bimanual movements during mirror therapy should in principle, combine the potential benefits of bilateral movement training (Stoykov & Corcos, 2009). Bilateral arm training after stroke has been shown to improve motor recovery (Cauraugh et al., 2010; Stewart et al., 2006). According to Cohn (1951) and Cunningham et al. (2002)'s behavioural investigation, when the paretic limb is moved simultaneously and synchronously with the nonparetic limb, the paretic limb's movement improves more than when the paretic limb is moved alone. This bimanual movement training builds on influential bimanual coordination research showing that movements of both hands tend to become coupled (Kelso et al., 1979; Swinnen & Gooijers, 2015). Given these benefits, numerous mirror therapy studies appear to have encouraged bimanual execution while moving the affected limb as much as they could (Dohle et al., 2009; Hiragami et al., 2013; Michielsen et al., 2011; Yavuzer et al., 2008).

However, the drawbacks of bimanual execution during mirror therapy have also been pointed out. Although being supported by neurophysiological studies, the effectiveness of bilateral training itself for stroke has been debated (Hatem et al., 2016; Pollock et al., 2014; Rose & Winstein, 2004). Since each stroke survivor has a different lesion and level of impairment, the effectiveness of bilateral training may vary for different groups of patients. It has been suggested that bimanual execution may split attention between the hands, resulting in less attention being directed to the affected limb (Morkisch et al., 2019). Additionally, McCabe (2011) highlights that the addition of mirror visual feedback to bimanual execution may induce unpleasant feelings caused by incongruency of the hands.

Given that the aim of mirror therapy following stroke is to improve performance/function in the affected limb, it is of clear interest to examine the performance of the affected (unseen) limb 'during' mirror therapy. In this study, the aim was to conduct a preliminary and exploratory study with a small number of stroke survivors. Consistent with the previous chapters, the focus of this was on examining the performance of the unseen hand in individuals with hemiparetic stroke when they make bimanual movements with mirror visual feedback.

Methods

Participants

Three individuals with left hemiparetic stroke (two men and one woman) from the Dream Rehabilitation Centre in Seoul, Korea, volunteered to participate in the study. General information for each participant is reported in Table 4.1. None of the participants had any abnormalities in muscle tone (Modified Ashworth Scale grade 0). They all had good motor function (Fugl-Meyer Assessment for Upper Extremity), good cognitive function (Mini-Mental State Examination), no anosognosia (Catherine Bergego Scale), and were without visual impairment. All were able to follow instructions and perform the task. However, Participant 3 showed signs of visuo-spatial neglect; in the line bisection test, eight lines were biased to the right. All participants were naïve to the purpose of the study. The study was approved by the Sahmyook University Ethics Committee. Participants provided written informed consent prior to taking part.

	Patient 1	Patient 2	Patient 3
Age	70	47	47
Gender	Male	Male	Female
Diagnosis	Right thalamic ICH & IVH	Traumatic subdural hemorrhage	Bilateral pons ICH
Chief Complaint	Left hemiparesis	Left hemiparesis	Left hemiparesis
Onset	5 months ago	4 years ago	3 months ago
Mini Mental State Examination (MMSE)	25/30	29/30	26/30
Modified Ashworth Scale (MAS)	Elbow flexor(R/L) - Grade 0/Grade 0, Wrist flexor(R/L) – Grade 0/Grade 0	Elbow flexor(R/L) - Grade 0/Grade 0, Wrist flexor(R/L) – Grade 0/Grade 0	Elbow flexor(R/L) - Grade 0/Grade 0, Wrist flexor(R/L) – Grade 0/Grade0
Visual impairment	None	None	None
Range of Motion (ROM)	No limitation	No limitation	No limitation
Oxford muscle grading scale	Right side – 5/5, Left side – 4/5	Right side – 5/5, Left side – 4/5	Right side – 5/5, Left side - Shoulder & Elbow: Fair, Forearm & Hand: 3/5
Wolf motor function test (WMFT)	83/85	85/85	79/85
Fugl-Meyer Assessment Upper Extremity (FMA-UE)	Motor function - 66/66, Sensory – 22/24	Motor function - 66/66, Sensory – 24/24	Motor function - 62/66, Sensory – 23/24
Line bisection test	Normal	Normal	8 bisections deviated to right from the true centre
Catherine Bergego Scale	1/30	0/30	1/30

Table 4.1 General information of each patient (n = 3). In FMA-UE, Patient 1 reported some joint discomfort during passive motion on shoulder abduction and wrist flexion. Patient 3 demonstrated limited volitional movement of the hand to the lumbar spine and pronation/supination, as well as minor tremors and dysmetria on her left arm. Patient 3's shoulder flexion range was slightly restricted, and she complained of slight pain.
On the Catherine Bergego scale, Patient 1 shown minor neglect when adjusting his left sleeve or shoe, and Patient 3 was seen to occasionally collide with persons or subjects on the left side, such as doors or furniture.
** ICH: Intracerebral brain hemorrhage; IVH: Intraventricular hemorrhage.*

Apparatus

The experiment was conducted in the private physiotherapy room at the Dream Rehabilitation Centre. Limb movements were recorded at a sampling rate of 200 Hz using three motion capture cameras (Miqus, Qualisys Ltd., Sweden) to track 14mm reflective spherical markers attached to the nail of each index finger using double-sided sticky tape.

A double-sided mirror (width 45cm x height 55cm) was placed perpendicular to the table and, aligned to the participant's mid-sagittal plane using bespoke wooden mounts. Between the double-sided mirrors, there was a piece of white fabric large enough to cover the mirror. In the mirror condition, the fabric was removed and the participants were instructed to gaze at the far target in the mirror. In conditions where no reflection was required, the mirror surface was covered with the fabric. The gaze point was marked on the cloth by affixing a sticker to the point comparable with where the participant gazed at the far target during the mirror conditions. A white-surfaced table was prepared and a line drawn on the midline of the table to denote the location of the mirror. Based on this line, two dots were marked with stickers on each side 20 cm away from the line. The two dots (1cm diameter) functioned as targets to guide the reciprocal bimanual movements. The near target (closer to the participant) was positioned 30 cm from the table edge; the far target was positioned 15cm from the near target, and 45 cm away from the table edge (see Figure 4.1).

Figure 4.1 Experimental setting. A double-sided mirror was placed in the centre of the white table, and the mirror visual feedback was blocked during vision conditions with a fabric placed between the mirrors. Two targets were placed on both sides of the mirror, the near target was positioned 30cm away from the body, and the far target was positioned 45cm away from the body. Bimanual repetitive aiming task was instructed for 15 seconds, and movement was tracked by a motion capture system.

Task, design, and procedure

The approach here was to largely replicate that followed in the previous chapter for unimpaired participants performing repetitive aiming movements (see Chapter 3). During the study, each trial required participants to make mirror symmetrical movements with their upper limbs, their index fingers moving between the near and far targets with both hands for 15 seconds. The frequency of movements was not controlled strictly, but participants were instructed to complete one cycle (i.e. from near target to far target to near) per second.

Each trial began with the participant's index fingers positioned on the far target. The examiner helped position the (unseen) hand behind the mirror. To prevent participants from looking at the position of their 'unseen' hand between trials, both hands were placed under the table during this period. If the participant touched the mirror or wooden mount with the unseen hand during the trial, the trial was abandoned at that point, the participant then placed his hands below the table and waited for the next trial.

To avoid fatigue, participants performed just 12 trials during the experiment under four conditions (three trials per condition). The four conditions were as follows;

- right hand visible with a mirror (*Right Mirror*),
- right hand visible without a mirror (*Right Vision*),
- left hand visible with mirror (*Left Mirror*),
- left hand visible without a mirror (*Left Vision*).

Conditions were randomised across trials. For the *Mirror* conditions, the reflective surface of the mirror was on the same side as the participant's head. For the *Vision* conditions, the mirror was covered with a white cloth so that the fabric with the fixation point was on the same side as the participant's head. Even if the unseen hand did not move at all during the trial, all scheduled trials were carried out to the end as planned. However, when the unseen hand did not move (occurred in the right mirror condition from Patient 3), three additional trials were conducted to obtain the unseen hand movement under the same condition. The participant was reminded to move the unseen hand during the trial before beginning the additional trial. The number of trials in which there was no movement of the unseen hand was counted, and after the scheduled trials, additional trials were completed to obtain equal amounts of data demonstrating movement of the unseen hand.

Before commencing the experiment, demographic and clinical information was gathered for all participants, and participants read the written instructions about the procedure of the experiment. Any accessories on the hand and wrist were removed, and any questions regarding the procedure were answered. Participants completed one practice trial for each condition before the actual task. To get used to the aiming pace, a metronome was set to 120Hz during practice. Once experimental trials began, the researcher provided verbal “go” and “stop” signals to indicate the start and finish of trials. Between the trials, there was a short break and a scheduled break after six trials.

Data analysis

Kinematic data were exported from the motion capture system and analysed via bespoke software (Matlab 2021b, Mathworks Inc., Natick, MA, USA). Signals were rectified and filtered with a 4th-order low-pass Butterworth filter using a cut-off of 20 Hz.

The main variables of interest were:

Positional drift - The furthest point reached from the far target in each trial for all participants and calculated via the straight-line length to the far target (in mm).

Straight-line distance - The direct distance from the near target aimed position to the far target aimed position was calculated with a 2-dimensional straight line for all movements (in mm).

Aiming error – The seen hand's aiming error was measured as the straight-line distance from the far target for each related aiming movement.

The aiming error of the unseen hand was measured as the straight-line distance from the predicted target for each related aiming movement. The relative positions of the predicted target and the unseen hand were found based on the analytical method suggested in the previous chapter (See Chapter 3 result section 4).

Positional drift was the primary outcome, with straight-line distance and aiming error as secondary outcomes.

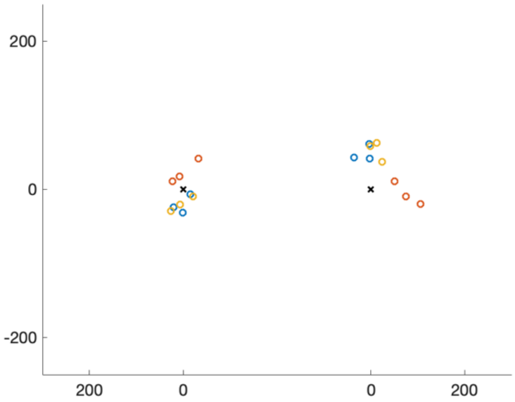
Statistical analysis

Data were analysed by using SPSS (IBM SPSS Statistics, Version 28.0. Armonk, NY, USA) and all normality checks were conducted. The data were normally distributed and appropriate for analysis using parametric tests. Mean values were calculated for each trial and entered for analysis as an observation. Data were analysed via a 2 × 2 × 2 × 3 ANOVA; the factors of interest were; *Head side* [left, right] × *Mirror* [mirror, vision] × *Hand* [seen, unseen] × *Patient [1, 2, 3]* with repeated measures for the first three factors. The interactions between simple effects were analysed with multiple comparison subject to Bonferroni correction. The threshold for statistical significance was set to $p < 0.05$. Where there was a significant main effect for the *Patient* factor or a related interaction, univariate analyses were conducted for each participant. The analysis was repeated at the participant level with entering the data from each aiming movement in the trial.

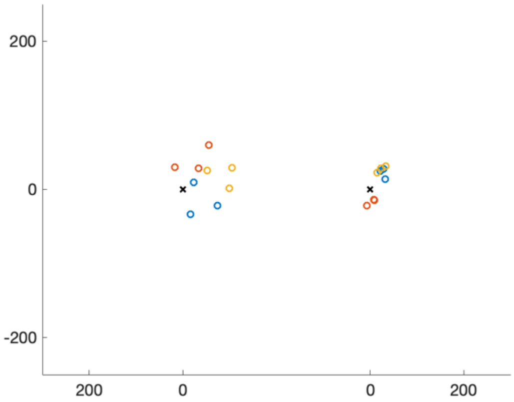
Results

Positional drift

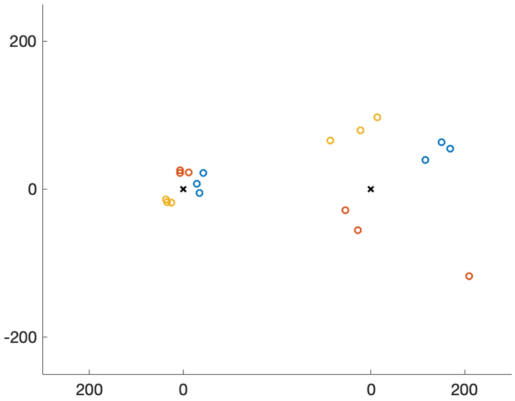
Figure 4.2 shows the furthest points reached away from the far target for each individual for each hand and from every trial for each condition. There were significant main effects of *Mirror*, $F(1,6) = 22.66$, $p = 0.003$, $\eta_p^2 = 0.791$, *Hand*, $F(1,6) = 72.23$, $p < 0.001$, $\eta_p^2 = 0.923$ but no significant main effect for *Patient*, $F(2,6) = 0.007$, $p = 0.993$, $\eta_p^2 = 0.002$. There were also *Mirror* x *Hand* interaction, $F(1,6) = 19.39$, $p = 0.005$, $\eta_p^2 = 0.764$, and *Head Side* x *Mirror* x *Patient* interaction, $F(2,6) = 5.57$, $p = 0.043$, $\eta_p^2 = 0.650$. The *Mirror* x *Hand* interaction is explained by the impact of the *mirror* on the *unseen* hand. The positional drift of the *seen* hand was comparable regardless of whether the mirror was in place or not, $F(1,6) = 0.93$, $p = 0.372$, $\eta_p^2 = 0.134$; however, positional drift of the *unseen* hand was significantly greater when the mirror was in place, $F(1,6) = 21.50$, $p = 0.004$, $\eta_p^2 = 0.782$. Given the interaction including the *Participant* factor, data were subsequently analysed for each participant separately. Here, separate ANOVAs were used for each participant and data from each movement completed was entered as an observation.



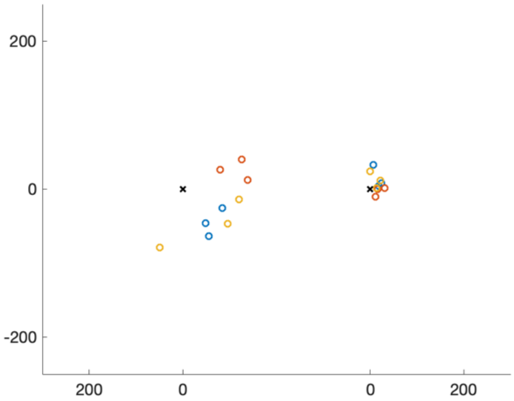
4.2-a Left Vision



4.2-c Right Vision



4.2-b Left Mirror



4.2-d Right Mirror

Figure 4.2 Positional drift. Dots represent the furthest points from far target on every trial as a function of Head side, Mirror and Hand. The dots of each patient are colour-coded in blue for patient 1, red for patient 2, and yellow for patient 3. Far targets on both sides are marked as 'x'. Positional drift of the unseen hand is indicated by dots near the right 'x' mark in the left conditions and by dots near the left 'x' mark in the right conditions. This figure illustrates that in mirror conditions, the unseen hand's furthest points from the far target are farther away than in vision conditions (also see Fig. 4.3).

Patient 1

There were significant main effects of *Head Side*, $F(1,16) = 10.41$, $p = 0.005$, $\eta_p^2 = 0.394$, *Mirror*, $F(1,16) = 27.23$, $p < 0.001$, $\eta_p^2 = 0.630$, *Hand*, $F(1,16) = 63.79$, $p < 0.001$, $\eta_p^2 = 0.799$.

There were also a *Head side* x *Mirror* interaction, $F(1,16) = 11.87$, $p = 0.003$, $\eta_p^2 = 0.426$, *Head side* x *Hand* interaction, $F(1,16) = 9.29$, $p = 0.008$, $\eta_p^2 = 0.367$, and *Mirror* x *Hand* interaction, $F(1,16) = 26.67$, $p < 0.001$, $\eta_p^2 = 0.625$. Figure 4.3 (left) describes the main effects and interactions. The positional drift of the *seen* hand was comparable regardless of whether the mirror was in place or not, $F(1,8) = 0.006$, $p = 0.939$, $\eta_p^2 = 0.001$. However, the positional drift of the *unseen* hand was significantly greater when the mirror was in place, $F(1,8) = 30.49$, $p < 0.001$, $\eta_p^2 = 0.792$. The presence of a mirror caused significant positional drift when the unseen hand was the unimpaired right hand, $F(1,8) = 34.56$, $p < 0.001$, $\eta_p^2 = 0.812$, but no significance was found when the unseen hand was the impaired left hand, $F(1,8) = 1.72$, $p = 0.226$, $\eta_p^2 = 0.177$.

Patient 2

Across the experiment, positional drift was greater in the unseen hand (mean = 92.85 $\pm$ 56.87mm) than in the seen hand (mean = 24.21 $\pm$ 10.37mm), leading to a substantial main effect of *Hand*, $F(1,16) = 16.91$, $p < 0.001$, $\eta_p^2 = 0.514$. As can be seen in Figure 4.3 (centre), the presence of a mirror caused significant positional drift of the unseen hand when the unseen hand was the impaired left hand, $F(1,8) = 8,13$, $p = 0.021$, $\eta_p^2 = 0.504$. but the significance has not been found when the unseen hand was the unimpaired right hand, $F(1,8) = 0.32$, $p = 0.588$, $\eta_p^2 = 0.038$.

Patient 3

There were significant main effects of *Mirror*, $F(1,16) = 5.79$, $p = 0.029$, $\eta_p^2 = 0.266$, and *Hand*, $F(1,16) = 106.32$, $p < 0.001$, $\eta_p^2 = 0.869$. There were also a *Head side* x *Hand* interaction, $F(1,16) = 5.10$, $p = 0.038$, $\eta_p^2 = 0.242$ and *Mirror* x *Hand* interaction, $F(1,16) = 9.10$, $p = 0.008$, $\eta_p^2 = 0.362$. Figure 4.3 (right) describes the main effects and interactions. When the head was to the right, there was no *Mirror* x *Hand* interaction, $F(1,8) = 3.27$, $p = 0.108$, $\eta_p^2 = 0.290$. However, when the head was placed to the left, there was a *Mirror* x *Hand* interaction, $F(1,8) = 7.84$, $p = 0.023$, $\eta_p^2 = 0.495$. Here, the seen impaired hand was comparable regardless of the presence of a mirror, $F(1,4) = 1.76$, $p = 0.255$, $\eta_p^2 = 0.306$, while the unseen unimpaired right hand showed greater positional drift in the presence of a mirror, $F(1,8) = 18.17$, $p = 0.013$, $\eta_p^2 = 0.820$.

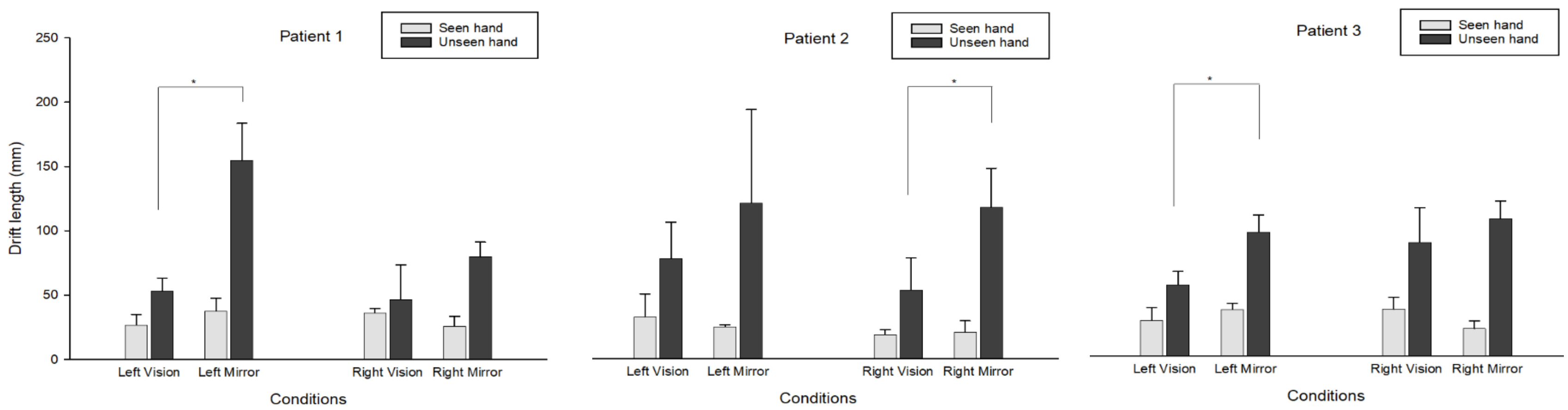


Figure 4.3 Mean drift length of each patient as a function of Head side, Mirror and Hand. The positional drift of the seen hand was comparable regardless of whether the mirror was in place or not. However, the positional drift of the unseen hand was greater when the mirror was in place. There was no statistically significant difference between patients ($p = 0.993$). Error bars denote standard error, and asterisks denote statistical significance

	Left Vision		Left Mirror		Right Vision		Right Mirror	
	Seen hand	Unseen hand	Seen hand	Unseen hand	Seen hand	Unseen hand	Seen hand	Unseen hand
Patient 1	26.69 (8.44)	53.04 (10.27)	37.62 (9.82)	154.77 (28.78)	36.12 (3.55)	46.48 (26.96)	25.89 (7.45)	79.75 (11.49)
Patient 2	32.71 (17.88)	78.19 (28.26)	24.81 (1.72)	121.39 (103.06)	18.74 (3.95)	53.57 (24.95)	20.57 (8.89)	118.26 (30.26)
Patient 3	27.74 (10.11)	55.57 (10.19)	36.31 (4.77)	96.55 (13.16)	36.49 (9.09)	88.47 (26.91)	21.26 (6.00)	106.80 (13.82)

Table 4.2 Mean (and standard error) values of positional drift from each patient.

Straight-line distance

The ANOVA revealed the following interactions; *Head Side* x *Patient*, F(2,6) = 13.13, p = 0.006, η_p^2 = 0.814, *Head Side* x *Mirror*, F(1,6) = 9.51, p = 0.022, η_p^2 = 0.613, *Head Side* x *Mirror* x *Patient*, F(2,6) = 8.85, p = 0.016, η_p^2 = 0.747, *Head Side* x *Hand* x *Patient*, F(2,6) = 8.11, p = 0.020, η_p^2 = 0.730, *Mirror* x *Hand*, F(1,6) = 15.43, p = 0.008, η_p^2 = 0.720, and *Head Side* x *Mirror* x *Hand* F(1,6) = 11.59, p = 0.014, η_p^2 = 0.659.

Given the multiple interactions including the *Patient* factor, data were subsequently analysed for each patient separately. Here, separate ANOVAs were used for each patient and data from each movement completed entered as an observation.

Patient 1

Across the experiment, mean straight-line distance was longer when the head was on the left (mean = 157.99 $\pm$ 15.62mm) than when the head was on the right (mean =

143.83 ± 17.57mm), leading to a significant main effect of *Head Side*, $F(1,230) = 32.31$, $p < 0.001$, $\eta_p^2 = 0.123$. Additionally, the seen hand travelled farther (mean = 157.35 ± 10.35mm) than the unseen hand (mean = 144.48 ± 21.56mm), $F(1,230) = 28.32$, $p < 0.001$, $\eta_p^2 = 0.110$. However, *Head side* x *Hand*, $F(1,230) = 41.85$, $p < 0.001$, $\eta_p^2 = 0.154$ and *Mirror* x *Hand*, $F(1,230) = 15.51$, $p < 0.001$, $\eta_p^2 = 0.063$ interactions suggested a more complex relationship between factors. Figure 4.4 (left) describes the main effects and interactions. When the head was on the right, the differences in straight-line distance between both hands were greater, $F(1,116) = 130.93$, $p < 0.001$, $\eta_p^2 = 0.530$ than when the head was on the left, $F(1,114) = 0.44$, $p = 0.507$, $\eta_p^2 = 0.004$. In the right head side conditions, when the paretic hand became the unseen hand, the unseen hand always travelled a significantly shorter distance than the seen hand, but the distance was shorter with the mirror than without it, $F(1,58) = 9.66$, $p = 0.003$, $\eta_p^2 = 0.143$.

Patient 2

There were significant main effects of *Head Side*, $F(1,250) = 67.02$, $p < 0.001$, $\eta_p^2 = 0.211$, and *Mirror*, $F(1,250) = 19.44$, $p < 0.001$, $\eta_p^2 = 0.072$. There were also a *Head side* x *Hand* interaction, $F(1,250) = 88.84$, $p < 0.001$, $\eta_p^2 = 0.262$, *Mirror* x *Hand* interaction, $F(1,250) = 98.98$, $p < 0.001$, $\eta_p^2 = 0.284$, and *Head Side* x *Mirror* x *Hand* interaction, $F(1,250) = 7.51$, $p = 0.007$, $\eta_p^2 = 0.029$. As may be seen in Figure 4.4 (centre), Movements of the unseen left (impaired) limb were hypermetric in the right vision condition, $F(1,62) = 114.69$, $p <.0001$, $\eta_p^2 = 0.649$ – whereas movements of the unseen right (unimpaired) limb were hypometric in the left mirror condition, $F(1,64) = 48.21$, $p < .0001$, $\eta_p^2 = 0.430$.

Patient 3

Across the experiment, the mean straight-line distance was greater when the head was on the right side (mean = 166.94 $\pm$ 27.84mm) than when the head was on the left side (mean = 147.06 $\pm$ 19.92mm), leading to a significant main effect of *Head Side*, $F(1,90) = 21.72$, $p < 0.001$, $\eta_p^2 = 0.194$. However, *Head side* x *Mirror*, $F(1,90) = 15.98$, $p < 0.001$, $\eta_p^2 = 0.151$, and *Mirror* x *Hand*, $F(1,90) = 12.60$, $p < 0.001$, $\eta_p^2 = 0.123$ interactions suggested a more complex relationship between factors. The results of the complex interaction are shown in Figure 4.4 (right). When the head was to the left, there was no *Mirror* x *Hand* interaction, $F(1,50) = 0.26$, $p = 0.610$, $\eta_p^2 = 0.005$. However, when the head was placed to the right, there was a *Mirror* x *Hand* interaction, $F(1,40) = 16.31$, $p < 0.001$, $\eta_p^2 = 0.290$. Here, the seen right (unimpaired) hand travelled a smaller distance than the unseen hand in the vision condition, $F(1,20) = 5.13$, $p = 0.035$, $\eta_p^2 = 0.204$. In the mirror condition, the straight-line distance of the unseen left (impaired) hand was smaller than the seen hand, $F(1,20) = 14.61$, $p = 0.001$, $\eta_p^2 = 0.422$.

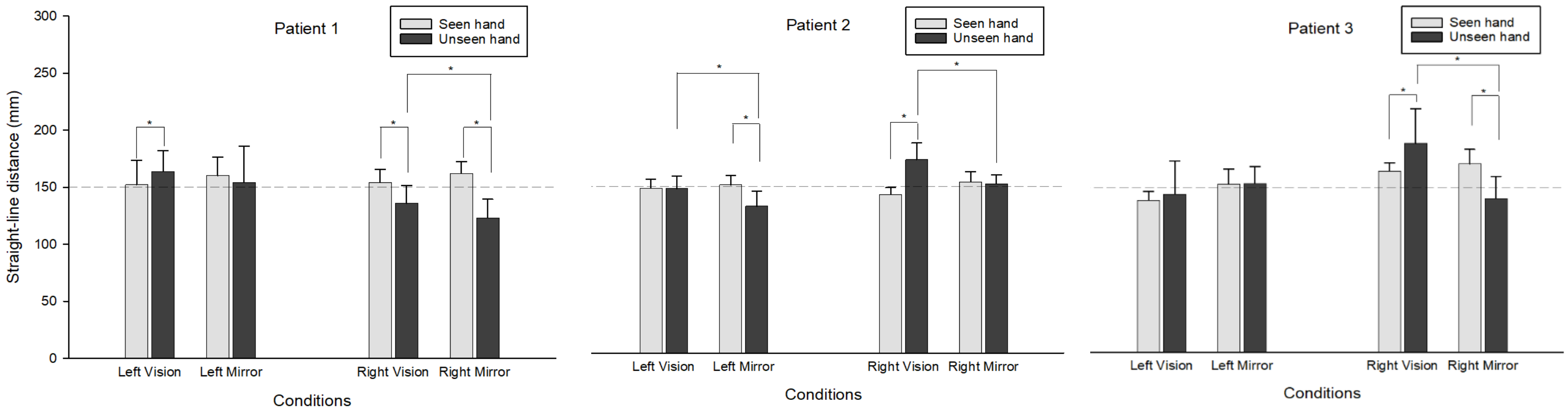


Figure 4.4 Mean straight-line distance as a function of Head side, Mirror and Hand. When the impaired limb becomes the unseen hand, the unseen hand's travelled distance was significantly reduced by the presence of a mirror in all three patients. The reference line drawn at 150 mm represents the straight-line distance between two aimed targets. Error bars denote standard error, and asterisks denote statistical significance.

	Left Vision		Left Mirror		Right Vision		Right Mirror	
	Seen hand	Unseen hand	Seen hand	Unseen hand	Seen hand	Unseen hand	Seen hand	Unseen hand
Patient 1	152.32 (16.98)	163.96 (11.59)	160.72 (12.55)	154.99 (25.22)	154.34 (5.31)	135.95 (2.66)	162.04 (3.74)	123.01 (15.58)
Patient 2	148.41 (3.66)	148.16 (5.17)	151.04 (7.76)	132.63 (9.63)	142.47 (0.88)	173.89 (12.55)	154.05 (7.04)	152.27 (6.39)
Patient 3	137.98 (4.19)	146.04 (29.98)	153.16 (1.12)	152.68 (10.73)	165.42 (3.21)	188.86 (13.67)	171.65 (10.58)	139.09 (22.74)

Table 4.3 Mean (and standard error) values of straight-line distance from each patient.

Aiming error

Figures 4.5 and 4.6 show all aimed positions at the far target and predicted target with the seen and unseen hands, respectively, for each individual and from every trial for each condition. There were significant main effects of *Hand*, F(1,6) = 27.51, p = 0.002, η_p^2 = 0.821, and *Patient*, F(2,6) = 7.17, p = 0.026, η_p^2 = 0.705. There were also the following interactions; *Head side* x *Patient* , F(2,6) = 8.34, p = 0.019, η_p^2 = 0.735; *Head side* x *Hand*, F(1,6) = 15.95, p = 0.007, η_p^2 = 0.727; *Head Side* x *Hand* x *Patient*, F(2,6) = 18.54, p = 0.003, η_p^2 = 0.861; *Head Side* x *Mirror* x *Hand* F(1,6) = 7.49, p = 0.034, η_p^2 = 0.555 and *Head Side* x *Mirror* x *Hand* x *Patient,* F(2,6) = 8.26, p = 0.019, η_p^2 = 0.734.

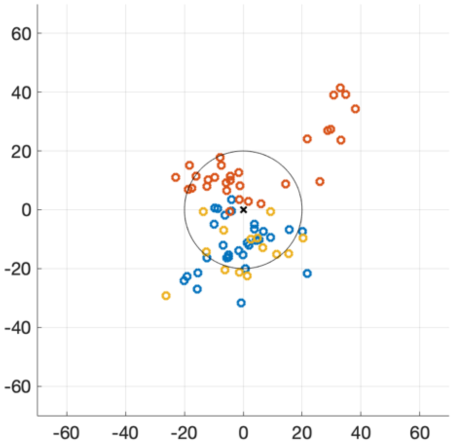
Given these effects and the differences that appeared between the three patients and related interactions, data were subsequently analysed for each patient separately. Here, separate ANOVAs were used for each patient and data from each movement completed was entered as an observation. Figure 4.7 shows the main effect and interaction in aiming error for each participant.

Patient 1

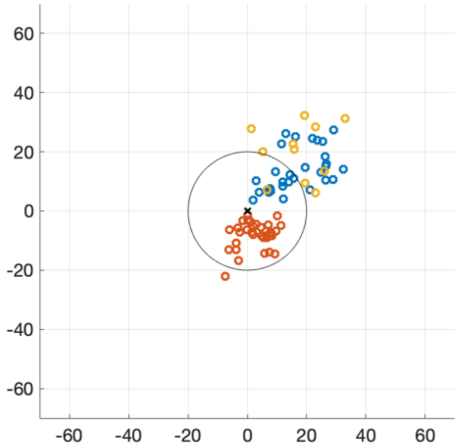
Across the experiment, the mean aiming error was larger in the unseen hand (mean = 23.77 $\pm$ 13.36mm) than the seen hand (mean = 19.49 $\pm$ 9.37mm), leading to a significant main effect of *Hand*, $F(1,206) = 8.79$, $p = 0.003$, $\eta_p^2 = 0.041$. There was also a *Head Side* x *Mirror* interaction, $F(1,206) = 35.68$, $p < 0.001$, $\eta_p^2 = 0.148$. As shown in Figure 4.7 (left), the presence of a mirror when the head was on the left side resulted in a larger aiming error, $F(1,102) = 18.91$, $p < 0.001$, $\eta_p^2 = 0.151$.

Patient 2

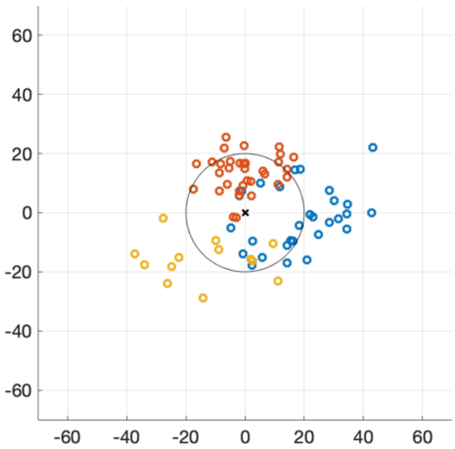
Across the experiment for patient 2, mean aiming error was larger in the unseen hand (mean = 17.27 $\pm$ 12.87mm) than in the seen hand (mean = 14.60 $\pm$ 9.78mm) leading to a significant main effect of *Hand*, $F(1,226) = 3.74$, $p = 0.054$, $\eta_p^2 = 0.016$. Additionally, mean aiming error was larger when the head was on the left side (mean = 20.04 $\pm$ 12.78mm) than when the head was on the right side (mean = 11.89 $\pm$ 8.10mm), $F(1,226) = 36.43$, $p < 0.001$, $\eta_p^2 = 0.139$. There was also a *Head Side* x *Mirror* interaction, $F(1,226) = 10.21$, $p = 0.002$, $\eta_p^2 = 0.043$.



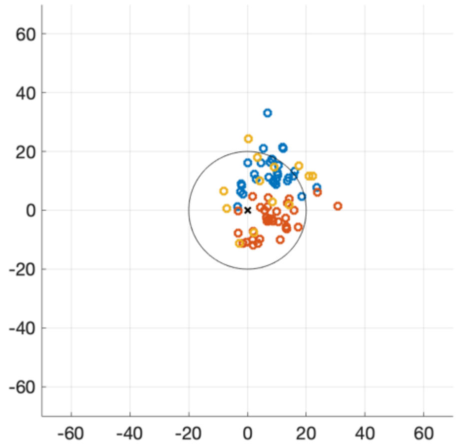
4.5-a Left Vision



4.5-c Right Vision

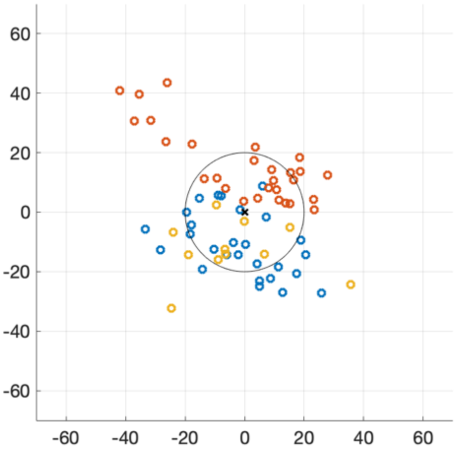


4.5-b Left Mirror

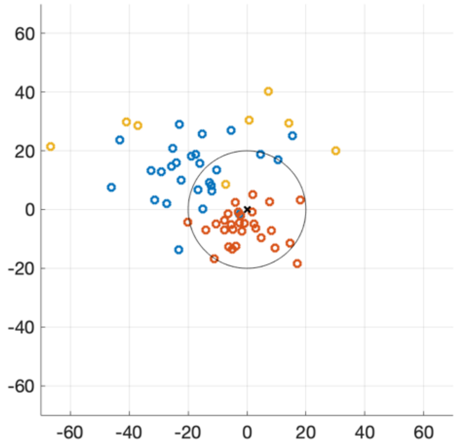


4.5-d Right Mirror

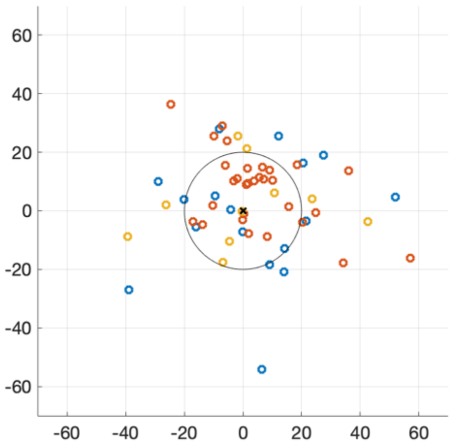
Figure 4.5 Seen hand's aiming error. Dots represent the seen hand's aimed position from the far target on every trial as a function of the Head side and Mirror. The far target is marked with a 'x' at 0,0, and a circle with a radius of 2 cm is drawn around for perspective. The dots of each patient were colour-coded in blue for Patient 1, red for Patient 2, and yellow for Patient 3. This figure shows that in the left conditions, the seen hand's aimed positions from the far target are farther away than in the right conditions.



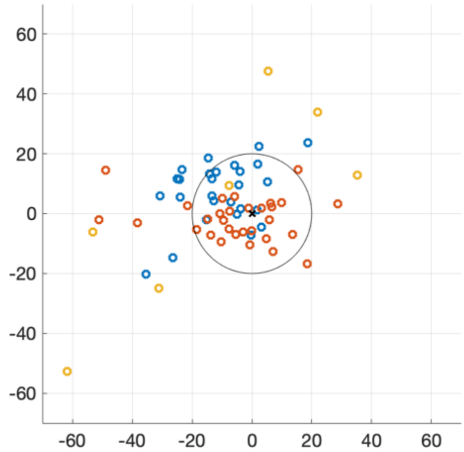
4.6-a Left Vision



4.6-c Right Vision



4.6-b Left Mirror



4.6-d Right Mirror

Figure 4.6 Unseen hand's aiming error. Dots represent unseen hand's aimed position from the predicted target (found from seen hand's error from the far target) on every trial as a function of the Head side and Mirror. The predicted target is marked with a 'x' at 0,0, and a circle with a radius of 2 cm is drawn for perspective. The dots of each patient were colour-coded in blue for Patient 1, red for Patient 2, and yellow for Patient 3.

Patient 3

Across the experiment for patient 3, mean aiming error was larger in the unseen hand (mean = 33.79 $\pm$ 20.89mm) than the seen hand (mean = 21.36 $\pm$ 8.59mm) leading to a significant main effect of *Hand*, $F(1,80) = 20.45$, $p < 0.001$, $\eta_p^2 = 0.204$. Additionally, mean aiming error was larger when the head was on the right side (mean = 32.96 $\pm$ 20.48mm) than when the head was on the left side (mean = 22.19 $\pm$ 10.53mm), $F(1,80) = 15.32$, $p < 0.001$, $\eta_p^2 = 0.161$. There were also *Head Side* x *Hand*, $F(1,80) = 26.22$, $p < 0.001$, $\eta_p^2 = 0.247$, and *Head Side* x *Mirror* x *Hand*, $F(1,80) = 6.47$, $p = 0.013$, $\eta_p^2 = 0.075$, interactions. As may be seen in Figure 4.7 (right), there was no significant difference in aiming error between the hands when the head was on the left side, $F(1,40) = 0.27$, $p = 0.606$, $\eta_p^2 = 0.007$; however the aiming error of the unseen (hemiparetic) hand was far greater when the head was on the right side, $F(1,40) = 34.80$, $p < 0.001$, $\eta_p^2 = 0.465$.

	Left Vision		Left Mirror		Right Vision		Right Mirror	
	Seen hand	Unseen hand	Seen hand	Unseen hand	Seen hand	Unseen hand	Seen hand	Unseen hand
Patient 1	16.07 (4.89)	19.38 (4.61)	22.46 (7.47)	26.49 (3.14)	22.23 (3.14)	25.88 (3.68)	16.28 (4.27)	18.07 (4.79)
Patient 2	22.42 (15.62)	24.20 (12.91)	16.14 (2.46)	19.65 (9.83)	10.01 (0.97)	10.62 (1.19)	11.36 (2.09)	15.53 (6.82)
Patient 3	18.48 (3.87)	21.03 (6.73)	24.82 (3.44)	22.35 (4.67)	27.27 (5.95)	40.06 (4.80)	15.28 (4.75)	51.59 (6.95)

Table 4.4 Mean (and standard error) values of aiming errors from each patient.

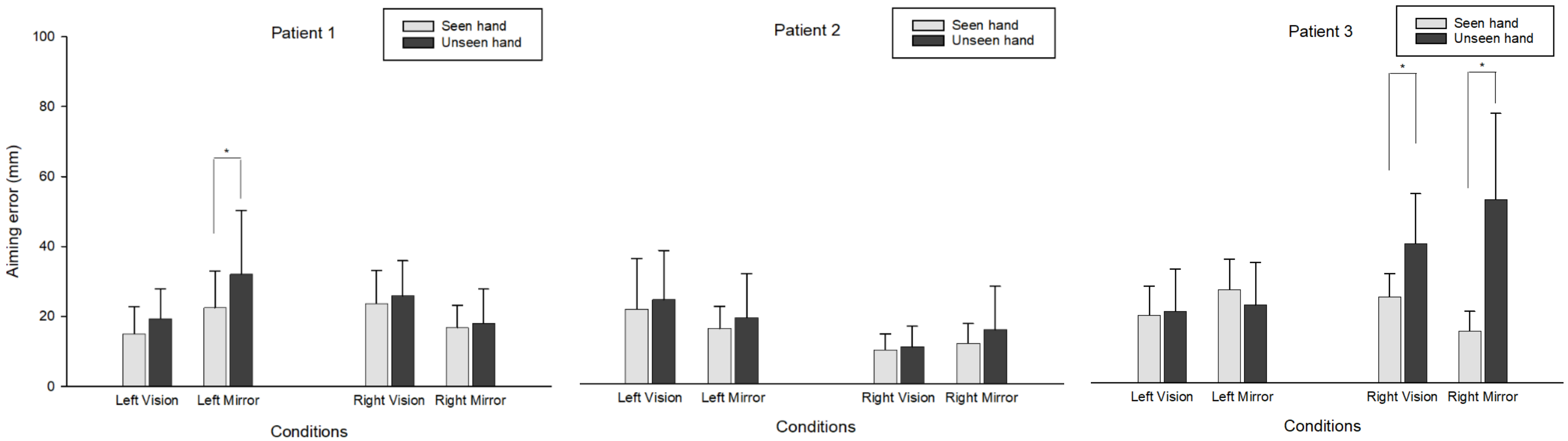


Figure 4.7 Aiming Error of each patient. The mean aiming error as a function of the Head side, Mirror and Hand. In all patient, mean aiming error was larger in the unseen hand than the seen hand. Patient 3 showed a significant difference from Patient 1 and 2 in the right mirror condition ($p < 0.001$ between Patient 3 and Patient 1, $p < 0.001$ between Patient 3 and Patient 2 and $p = 0.91$ between Patient 1 and Patient 2). Error bars denote standard error, and asterisks denote statistical significance.

Discussion

In this exploratory study, movement of the hands was examined during mirror visual feedback in three individuals with left hemiparesis following stroke. The approach to measurement of hand movements followed the approach taken in the previous chapter (Chapter 3) where unimpaired individuals were investigated. Positional drift previously identified in the unseen hand for unimpaired participants was also observed in the movements of all three stroke patients. A further observation related to the amplitude of movements was made (explored by straight-line distance). Here, when the paretic limb was the unseen hand, all participants demonstrated a significant reduction in movement amplitude (i.e. movements of the unseen hand became relatively *hypometric*) for the mirror condition relative to the vision condition.

Additionally, aiming error was observed. When the paretic limb was the unseen hand, the patient with unilateral spatial neglect showed significant aiming errors in the unseen hand with the mirror.

Rather than presenting a descriptive (case series) here, a statistical approach was taken that is relatively common in neuropsychological research (Crawford & Garthwaite, 2004; Shallice, 1988). This involved performing statistics on data from three individuals following stroke as group data and then examined the individual patient data to check whether patterns of data were consistent across different patients. This analytic approach is very similar to the one used by Husain et al. (2000)'s (also see Mattingley et al., 1998) study. This enabled the use of the same analysis procedure described in Chapter 3, with the added benefit of allowing the effects observed in each condition to be compared to the results of unimpaired individuals.

Furthermore, the experimental design of the present clinical study was the same as in Chapter 3, and the primary outcome was still positional drift. When targeting unimpaired individuals, the effect of the mirror on positional drift always showed 100% power in two or more people, and it also showed 100% power in the data of three stroke patients in this experiment. As a result, the strategy of initially analysing three people's data as group data demonstrates that mirrors can have the same impact on positional drift in both the unimpaired and impaired populations.

Individuals with hemiparetic stroke demonstrated positional drift of the unseen hand similar to unimpaired participants presented in Chapter 3. The unseen hand drifted more than the seen hand in the *Vision* condition, and the difference was even greater when the mirror was in place. The consistency here with unimpaired participants suggests the unseen hand was corrected in response to the movement of the seen hand.

While the positional drift data for stroke patients showed similarities with unimpaired participants, the straight-line distance and aiming error results were markedly different. The patients' results revealed intriguing outcomes when the impaired limb was hidden behind the mirror, and perhaps the most striking of these was the marked *motor extinction*. Motor extinction refers to motor behaviour that is analogous to sensory extinction that is a part of the neglect syndrome (Driver & Vuilleumier, 2001). At the behavioural level, it shows that when the patient performs a bimanual movement, the neglected side's motor output decreases or is absent (Punt & Riddoch, 2006). There are two possible explanations for the deficit in contralesional motor production found during motor extinction: failure of intention and failure of attention. Failure of intention is characterised by a failure to set the activation level of motor output, which may indicate hypometria, bradykinesia, and hypokinesia (delay to initiate movement) of the contralesional limb (Heilman, 2004). The attentional failure reflects underlying issues with monitoring the sensory consequences of movement. The lack of awareness of the contralesional movement might be represented as a movement deficit (Punt et al., 2013). Motor extinction may represent intentional or attentional failures, or both failures at the same time.

When the impaired limb was the unseen limb, all three patients demonstrated relatively hypometric movements in the Mirror condition compared to the Vision condition. This was an intriguing finding, especially given the relatively mild level of sensori-motor impairment shown by the patients on examination (see Table 1) and appeared to have some similarities with other behaviours that are observed in patients with left-sided hemiparesis (right brain damage).

Where movements of the impaired limb deteriorate during bilateral movement conditions, the term motor extinction (Punt et al., 2005) has been used to describe the behaviour because of the similarities with the more commonly referred to sensory extinction (Driver & Vuilleumier, 2001). In the three patients here, motor extinction was only elicited when the mirror was in place; why should this be the case? It seems likely that vision of the illusory limb in the mirror condition led to reduced attention (and awareness) towards the unseen limb, perhaps accounting for the deterioration in related motor control.

While this was true for all patients, it was most pronounced for Patient 3, who showed further related behaviour. Indeed, although the results section above show movement data for Patient 3, it was notable that this patient initially failed to move the impaired limb at all when it was unseen and the mirror was in place. Although prompting was able to elicit related movement, the patient seemed unaware of the akinesia, claiming that their arms were moving behind the mirror. This behaviour is reminiscent of recent accounts of anosognosia for paresis exposed via assessment of bimanual movements (Garbarini & Pia, 2013).

Observation of Patient 3 suggested they retained movement intention in the absence of movement production (Garbarini et al., 2013). Importantly, this was only the case in the mirror condition, movement of the illusory limb presumably heightening Patient 3's perception of movement in their impaired limb, distracting them from veridical sensory information informing them of the akinesia. With prompting (cueing), some movement occurred, but control remained markedly impaired in the mirror condition.

Although most marked in Patient 3, mirror-induced motor extinction could be observed in all three patients via the straight-line distance (movement amplitude) measure. For the aiming error measure, only Patient 3 showed markedly different behaviour to unimpaired participants (see Chapter 3). While Patients 1 and 2 demonstrated relatively hypometric movements of the impaired limb (when it was the unseen limb), their aiming movements were within the limits of the normality set. This was not the case for Patient 3, who demonstrated marked aiming errors with the impaired limb (when it was the unseen limb) for both Vision and Mirror conditions, the errors being most pronounced in the latter. However, whereas such errors in unimpaired individuals were interpreted as representing movements inconsistent with the mirror illusion, that is not the interpretation suggested for here. Rather, for Patient 3, these marked aiming errors appear to be simply a result of poor motor control.

In all three patients and particularly in Patient 3, one can only speculate what the implications for optimal mirror therapy might be. If mirror visual feedback is seen to reinforce anosognosia for paresis (as it appeared to do here), it seems unlikely that one would wish to encourage this, especially given advice that related difficulties should be addressed by encouraging affected patients to visually observe their deficits (Fotopoulou et al., 2009). More generally, whether patients who show motor extinction are better advised to execute movements unilaterally during mirror therapy remains to be determined, but one can clearly see an argument for this. Moreover, without a clear basis for the mechanisms underpinning the effectiveness of mirror therapy, researchers and clinicians will remain uncertain as to the optimal conditions for delivering this intriguing intervention.

Conclusion

This study investigated unseen hand movements during mirror visual feedback in 3 individuals with left hemiparetic stroke. All three patients exhibited unseen hand drift, which is consistent with previous study for unimpaired individuals. When the impaired limb was the unseen limb, all patients showed motor extinction, which was seen by aiming error and straight-line distance. Results revealed motor extinction features of intentional deficit (hypometric, high aiming error) due to attentional component (mirror visual feedback). In patient 3 with unilateral spatial neglect, motor extinction was most prominent, and there also appeared to be a loss of motor awareness. It may be preferable to direct unimanual execution during mirror therapy if motor extinction is noticeable in the impaired limb.

Chapter 5. Factors affecting the mirror illusion during mirror therapy? Optimising the illusory experience during mirror visual feedback in unimpaired individuals

Abstract

Patients recovering from hemiparetic stroke have been shown to benefit from mirror therapy in terms of improving their motor function. The clinical improvement in motor function may differ depending on the mirror therapy protocol used. Previous studies have shown that four parameters are influential: the size of the mirror (large and small), manipulation of objects (with or without), the complexity of action (simple and complex), and movement execution (unilateral and bilateral). This study examined the impact of these parameters on the subjective quality (believability) of the mirror illusion in unimpaired participants.

Forty healthy participants completed 16 different combinations of the four parameters during mirror visual feedback. Participants rated each trial for its level of *believability* on a 10-point Likert scale. A repeated measures ANOVA was used to examine the data.

The large mirror consistently elicited higher ratings than the small mirror. And while bimanual movements generally elicited higher ratings than unimanual movements, ratings for bimanual movements were significantly reduced when participants made complex movements with objects. This chapter attributed these results to the congruency of multisensory information. Conditions that elicit congruency between illusory information and other sensory inputs appear to maximise believability over the illusory hand. The findings of this study reveal the parameters maximising illusion believability in unimpaired participants and have implications for optimal mirror therapy conditions in patients' groups.

Introduction

Mirror therapy has been suggested as an effective intervention for the rehabilitation of paretic limbs in stroke survivors (Altschuler et al., 1999). It is most commonly employed as an intervention for the upper limb and has been shown to improve motor impairment and function of the paretic limb (Thieme et al., 2018). Despite numerous clinical trials, the precise mechanism of mirror therapy remains uncertain. Furthermore, many different protocols exist, and it remains unclear what the optimal approach may be.

Morkisch et al. (2019) conducted a meta-analysis to examine the impact of different mirror therapy protocols on the effectiveness of the intervention, examining motor function data from stroke survivors that were included in the Cochrane review (Thieme et al., 2018). Their analysis focused on three components: (i) small vs large mirror, (ii) unimanual vs bimanual movement execution, and (iii) use of an object or not.

Data from the meta-analysis suggested mirror therapy to be most effective when a large (rather than a small) mirror was used. Following the definition used by Kim and colleagues (2017), they classified the size of the mirror as a large mirror when it is larger than the size (50*40cm size) that reaches the minimum eye level. The use of large mirrors may help to make the illusion process more immersive (Ramachandran & Rogers-Ramachandran, 2019); the larger the mirror, the more obscured the limb behind the mirror becomes and perhaps allows greater focus on the hand reflected in the mirror. Additionally, the larger mirrors allow more of the limb to be reflected, facilitating a greater adaptation (Morkisch et al., 2017).

The meta-analysis also showed that encouraging patients to make only unimanual movements with the unaffected arm only (unimanual execution) was more effective than instructing patients to move both limbs together (bimanual execution). This finding is intriguing, not only because it differs from the initially proposed protocol for mirror therapy in individuals with hemiparetic stroke, but also because it discourages movement in the limb the intervention is designed to improve function in. When Altschuler et al. (1999) first proposed mirror therapy for stroke patients, they suggested moving both arms together and symmetrically. The impaired limb hidden behind the mirror was instructed to move as much as possible, and it was believed that this method could fulfil the purpose of mirror therapy by enhancing the movement of the impaired (unseen) limb. The results of the meta-analysis (Morkisch et al., 2019) therefore seem counterintuitive. It was proposed that the weaker effect for bimanual execution was due to the bilateral dispersion of attention during therapy (Morkisch et al., 2019).

Morkisch et al. (2019)'s meta-analysis also demonstrates that effectiveness was reduced when object manipulation is involved than when it is not. Tasks that manipulate objects are often described as task-oriented practice in the rehabilitation (Arya et al., 2015; Higgins et al., 2006; Michaelsen et al., 2006), and many studies recommended a task-oriented approach for upper limb rehabilitation in individuals with stroke (Bravi & Ellen Stoykov, 2007; da Silva et al., 2020; Veerbeek et al., 2014). This suggests outcomes for task-oriented training with real visual information for the impaired limb versus mirror therapy training (with illusory information) may differ considerably. The authenticity of the visual information appears to be a critical factor in completing an object manipulation task, as one needs to adapt hand movements in response to reliable visual information (Flanagan et al., 2006).

From another perspective, the impact of what is instructed with object manipulation may be more important than simply the involvement of an object. For example, Bai et al. (2019) reported that movement-based mirror therapy improved motor impairment more than task-based mirror therapy in subacute stroke survivors. The movement-based group were instructed to make simple joint movements without an object, such as joint flexion and extension, gripping and releasing, and finger tapping, while the task-based group were instructed to make relatively complex movements with objects, such as transferring cubes, placing pegs in holes and turning over paper cards. When comparing the tasks assigned to the two groups, it is clear that this may not simply be a result of object manipulation. The findings of this study indicate that both the complexity of movement required as well as the involvement of an object should be considered.

The impact of task complexity on illusory experience (using a 'task realism' scale) was examined under mirror visual feedback conditions for unimpaired participants (Rowe, 2019). Across twenty-five different bimanual tasks classified in multiple different ways, participants rated simple movements without object manipulation as being the most realistic.

Illusion strength appears to depend on the congruency of multiple sensory information. When sensory information from different modalities is congruent, sensory inputs are strengthened and facilitate behavioural responses (Alais et al., 2010). In contrast, where conflicts between sensory information occur, this appears to threaten the illusion (Wittkopf et al., 2019). Any incongruence against the illusory information, along with incongruence amongst sensory inputs, may undermine the illusion (Synofzik et al., 2006). A crossmodal illusion occurs when the senses received from one modality affect the senses received from other modalities, providing coherence to the ongoing perceptual experience (Bolognini et al., 2015). In the case of mirror therapy, visual information obtained through the mirror illusion affects the proprioceptive (Snijders et al., 2007) or tactile information (Katsuyama et al., 2018) from the unseen hand. As a result of multisensory integration, the presence of a mirror biases perception toward the (visual) illusory information (Holmes & Spence, 2005; Holmes et al., 2004).

The contribution of the crossmodal illusion during mirror visual feedback can be indicated through the investigation of the sense of embodiment (Ehrsson, 2020; Ernst & Bülthoff, 2004; Wittkopf et al., 2019). The sense of embodiment indicates how much one believes the hand reflected in the mirror as one's own unseen hand. Sense of embodiment encompasses three subcomponents. This includes whether the mirror image appears to be yours (ownership), whether you feel that the moving mirror image is under your control (agency), and whether you feel that the mirror image represents the location of the unseen hand (location) (Longo et al., 2008). However, embodiment can be simply investigated as a sense of realism (Rowe, 2019) or a peculiarity (Fink et al., 1999) in the mirror image during mirror visual feedback.

Beyond simply feeling that the image in the mirror is yours (ownership), the participant's believability more intuitively judges the embodiment of believing that the hand is your own. In other words, this is a direct question of self-identification, not just in terms of how participants recognise the movement of the illusory limb (Gallagher, 2000), but also in terms of how they can distinguish between self-generated action and movement on the exterior world (mirror) (Jeannerod, 2006).

The perception that the hand in the mirror is one's actual unseen hand becomes stronger when there is greater congruence between the sensory inputs (embodiment), but the perception becomes weaker when there is a higher incongruity (deafference) (Medina et al., 2015). The mismatch between motor intention/command and actual sensory feedback can also influence embodiment when there is movement during the mirror visual feedback (Jeannerod, 2006). As described in Chapter 3, the greater the congruency between the predicted and actual states, the stronger the perception that the illusory hand is one's actual unseen hand. The mismatches between sensory information lead to body representation and ultimately undermine rehabilitation outcomes (Matamala-Gomez et al., 2020).

This study aimed to investigate the believability over the illusory limb (sense of embodiment) and how this sense was modulated by manipulating four parameters that have been considered important in mirror therapy research (mirror size, movement execution, task complexity, object manipulation). Beyond the realism of the mirror image, the sense of embodiment investigates if the hand seen in the mirror is believed to be one's own hand.

Based on the findings, it was sought to address the implications for mirror therapy protocols and illustrate what the optimal mirror therapy protocol might be.

Methods

Participants

Forty right-handed (seventeen male; mean age: 21.2 years) participants from the undergraduate student body at the University of Birmingham volunteered to take part in the study. All participants were unimpaired and were naïve to the purpose of the study. The handedness of the participants was self-reported. The study was approved by the University of Birmingham's Science, Technology, Engineering and Mathematics Ethical Review Committee. Participants provided written informed consent prior to taking part.

Apparatus

The experiment was conducted at the Motor Cognition Laboratory, part of the School of Sport, Exercise, and Rehabilitation Sciences at the University of Birmingham. Two different sizes of landscape-oriented Perspex mirrors (50cm X 40cm or 25cm X 20cm) were used depending on the conditions. The mirrors were placed perpendicular to the table and aligned to the participant’s mid-sagittal plane using small bespoke wooden mounts. The large mirror (50cm X 40cm) had three wooden mounts, and the small mirror (25cm X 20cm) had one. The large and small mirrors were positioned so that the participant's dominant hand's reflection was within full visual range - with the centre of the mirror and their palm in line. The large mirror was fixed with its edge aligned with the table edge, while the small mirror was adjusted to fit each participant. Mirror positions were marked on the table and kept consistent during the experiment. Both hands were placed nine inches away from the mirror to avoid touching the mirror and wooden mounts during the trials (see Figure 5.1).

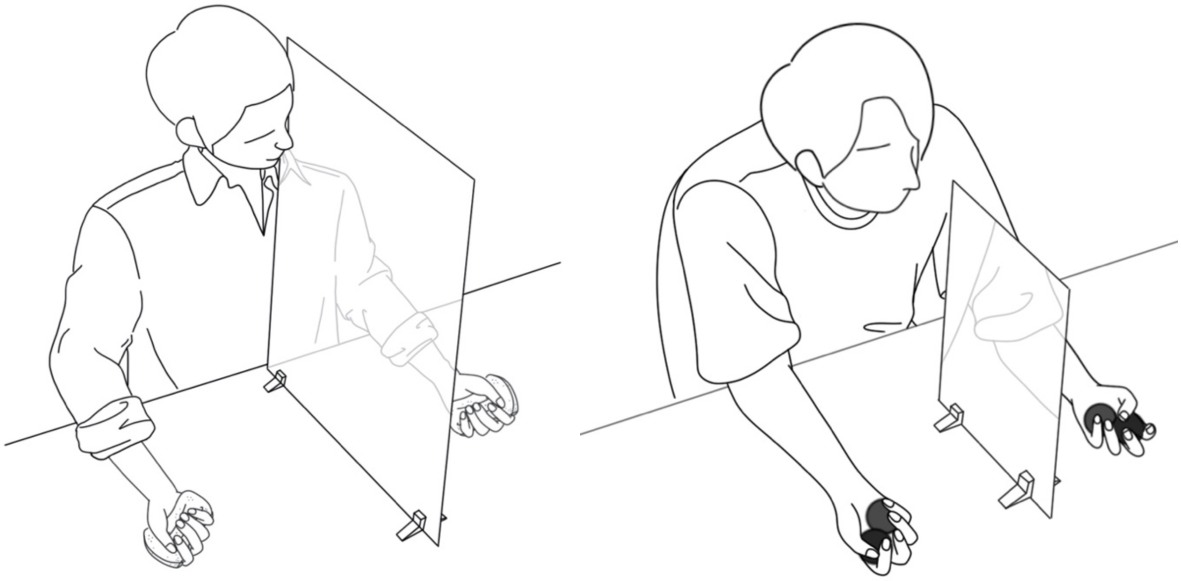


Figure 5.1 The left figure illustrates one of the conditions in which the participant looks into a large mirror while performing the simple task with manipulating the object. The right figure illustrates one of the conditions in which the participant looks into a small mirror while performing the complex task with manipulating the object. During the trial, participants were directed to look at their hand in the mirror, and both hands were placed 9 inches away from the mirror. Participants completed the task with both hands simultaneously during bimanual execution. However, in unimanual execution conditions, only the hand in front of the mirror (dominant hand) was instructed to move, and the hand behind the mirror did not move with the palm facing up.

Task, design and procedure

During the study, each trial required participants to perform self-paced repetitive movements for 20 seconds. Participants performed 48 trials during the experiment under 16 conditions; participants completed three trials per condition. Sixteen conditions were created by a combination of four parameters (See Table 5.1). Details of the parameters are as follows:

				Movement execution			
				Unimanual execution		Bimanual execution	
				Task complexity			
				Simple task	Complex task	Simple task	Complex task
Mirror size	Large mirror	Object manipulation	Without object	Unimanual simple task without object in large mirror	Unimanual complex task without object in large mirror	Bimanual simple task without object in large mirror	Bimanual complex task without object in large mirror
			With object	Unimanual simple task with object in large mirror	Unimanual complex task with object in large mirror	Bimanual simple task with object in large mirror	Bimanual complex task with object in large mirror
	Small mirror		Without object	Unimanual simple task without object in small mirror	Unimanual complex task without object in small mirror	Bimanual simple task without object in small mirror	Bimanual complex task without object in small mirror
			With object	Unimanual simple task with object in small mirror	Unimanual complex task with object in small mirror	Bimanual simple task with object in small mirror	Bimanual complex task with object in small mirror

Table 5.1 The sixteen conditions. The conditions were created by a combination of four parameters: (i) mirror size (large vs small), (ii) movement execution (unimanual vs bimanual), (iii) complexity of tasks (simple vs complex), and (iv) object manipulation (with object vs without object).

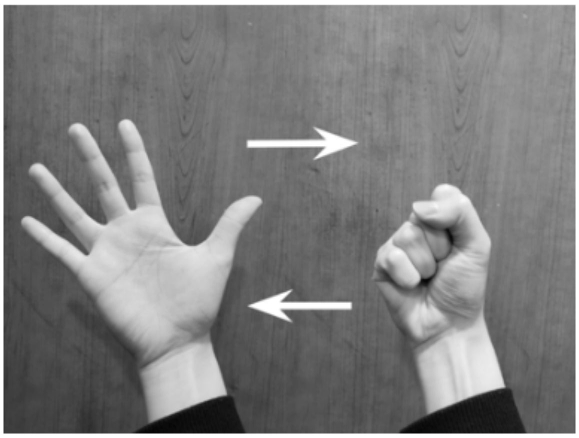
(i) Mirror size (large vs. small)

Large mirror and small mirror were used depending on the condition.

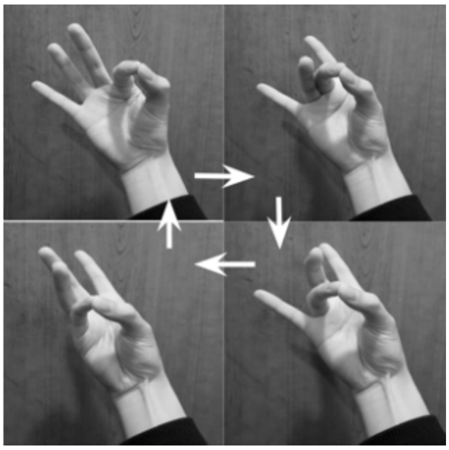
(ii) Movement execution (unimanual vs bimanual)

· Unimanual execution: The task was completed with only the dominant (right) hand in front of the mirror, while the unseen non-dominant (left) hand remained static. While performing unimanual execution and also manipulating an object, the object was not held in the unseen hand, which remained static with the palm facing up.

· Bimanual execution: The hands were instructed to move simultaneously, and while manipulating objects, both hands held objects of the same shape and size.

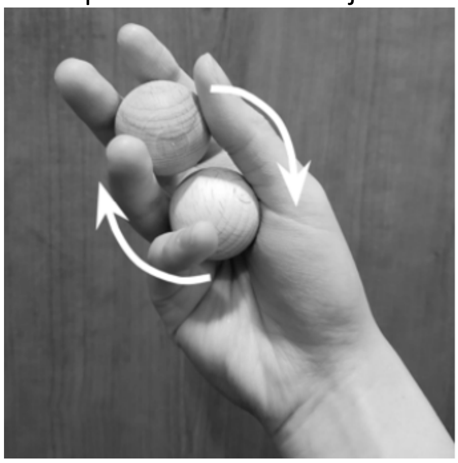


5.2-a Simple task without object



5.2-b Complex task without object

5.2-c Simple task with object



5.2-d Complex task with object

Figure 5.2 The four conditions combining task complexity and object manipulation parameters. For a 'simple task without object', participants were asked to open and close their fist repeatedly (Figure 5.2-a). For 'complex task without object', participants were asked to tap their thumb onto the index, middle, ring and little finger in order and repeat (Figure 5.2-b). For 'simple task with object', participants were asked to squeeze the sponge repeatedly with their palms (Figure 5.2-c). For 'complex task with object', participants were asked to rotate two wooden balls either clockwise with the dominant hand and anti-clockwise with the non-dominant hand (Figure 5.2-d).

(iii) Complexity of tasks (simple vs complex) and (iv) manipulation of objects (with vs without object)

· Simple task without object (see Figure 5.2-a).

· Complex task without object (see Figure 5.2-b).

· Simple task with object: A sponge (9cm X 4cm X 2cm) was given (see Figure 5.2-c).

· Complex task with object: Two wooden balls (2.5cm diameter) were given to each hand (see Figure 5.2-d).

Conditions were randomised across trials. In all conditions, participants were instructed to direct their vision to the reflection of the hand in the mirror. Fifteen seconds after the start of each trial, the experimenter asked the participants to rate their *believability* on a Likert scale with the following question. “How much do you believe the hand in the mirror feels like your left hand?” The question was answered with a number ranging from zero to ten. Zero implies ‘not at all’, whereas ten means ‘completely the same’. Once every eight trials, the entire question was posed; the remaining trials only asked for a "please rate from zero to ten" response.

Before commencing the experiment, participants completed the Edinburgh Handedness Inventory and read the written instructions about the procedure of the experiment. Any accessories on the hands and wrists were removed, and any questions regarding the procedure were answered. Participants completed a few practice trials before the experimental trials began in order to familiarise themselves with the procedure. Once experimental trials began, the researcher provided verbal “go” and “stop” signals to indicate the start and finish of trials. Between the trials, there was a short break and a scheduled break after 20 trials.

Statistical analysis

Data were analysed by using SPSS (IBM SPSS Statistics, Version 28.0. Armonk, NY, USA) and all normality checks were conducted. The data were normally distributed and appropriate for analysis using parametric tests. The dependent variable of interest was the participant's *ratings of believability*. The mean ratings for the three repetitions and for each participant were entered for statistical analysis. *Ratings of believability* data were analysed via a 2 × 2 × 2 × 2 (*Mirror* size [large, small] × *Movement execution* [unimanual, bimanual] × *Task complexity* [simple, complex] × *Object manipulation* [with an object, without object]) analysis of variance (ANOVA) with repeated measures. The interactions between simple effects were analysed with multiple comparison subject to Bonferroni correction. The threshold for statistical significance was set to $p < 0.05$.

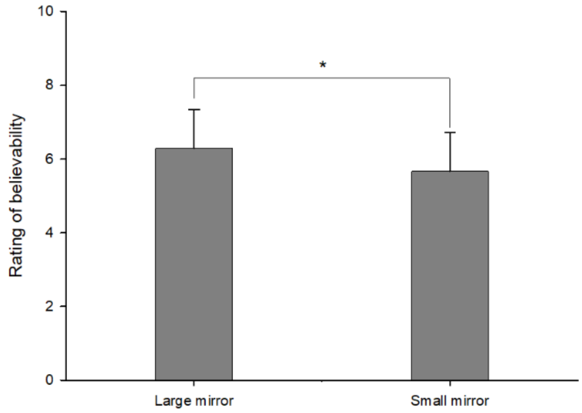
Results

Mirror size

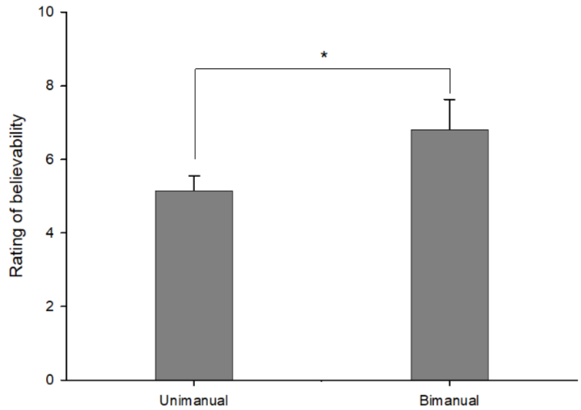
The believability was greater when the large mirror (mean = 6.29 $\pm$ 2.40) was in place than when replaced by the small mirror (mean = 5.67 $\pm$ 2.39), leading to a significant main effect of *Mirror size*, $F(1,39) = 34.23$, $p < 0.001$, $\eta_p^2 = 0.467$) (see Figure 5.3-a).

Movement execution

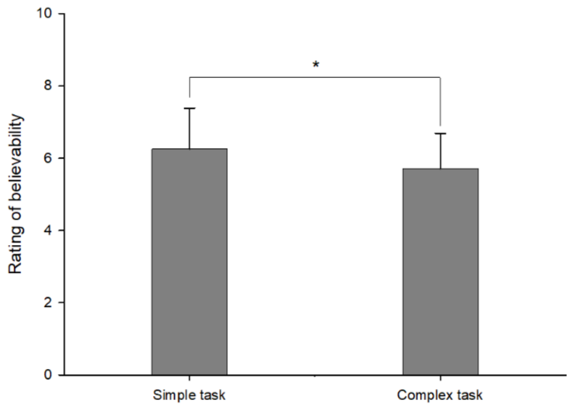
The believability was greater when the tasks were performed bimanually (mean = 6.81 $\pm$ 2.17) than the unimanual execution (mean = 5.15 $\pm$ 2.36), leading to a significant main effect of *Movement execution*, $F(1,39) = 37.85$, $p < 0.001$, $\eta_p^2 = 0.493$) (see Figure 5.3-b).



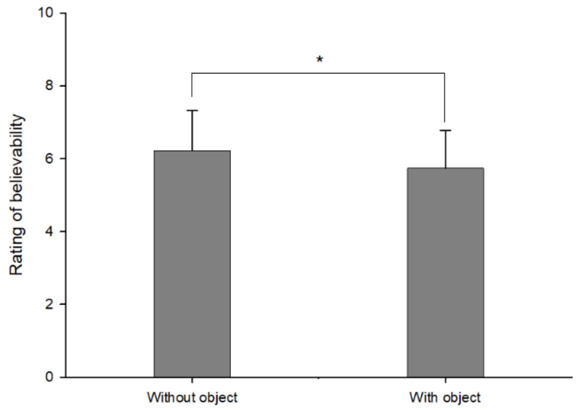
5.3-a Mirror size



5.3-b Movement execution



5.3-c Task complexity



5.3-d Object manipulation

Figure 5.3 Ratings of believability in each parameter. In this figure, the effects of each parameter are shown by comparing the two levels. The believability was rated out of a total of 10 points. The ratings of believability were shown to be greater for large mirror, bimanual execution, simple task, and when the object was not manipulated.

Task complexity

The believability was greater when the task was simple (mean = 6.25 $\pm$ 2.46) than when the task was complex (mean = 5.71 $\pm$ 2.34) leading to a significant main effect of *Task complexity*, F(1,39) = 18.02, p < 0.001, η_p^2 = 0.316) (see Figure 5.3-c).

Object manipulation

The believability was greater when the tasks were performed without object (mean = 6.22 $\pm$ 2.38) than when performed with object (mean = 5.74 $\pm$ 2.42) leading to a significant main effect of *Object manipulation*, F(1,39) = 13.31, p < 0.001, η_p^2 = 0.254) (see Figure 5.3-d).

However, *Movement execution* x *Task complexity*, F(1,39) = 29.07, p < 0.001, η_p^2 = 0.427, *Movement execution* x *Object manipulation*, F(1,39) = 6.78, p = 0.013, η_p^2 = 0.148, *Task complexity* x *Object manipulation*, F(1,39) = 36.15, p < 0.001, η_p^2 = 0.481, and *Movement execution* x *Task complexity* x *Object manipulation*, F(1,39) = 11.17, p = 0.002, η_p^2 = 0.223 interactions suggested a more complex relationship between factors. The results of the three-way interaction are shown in Figure 5.4.

When performing unimanual execution, the believability between simple and complex tasks with objects, F(1,39) = 3.96, p = 0.054, η_p^2 = 0.092 or without objects, F(1,39) = 0.065, p = 0.8, η_p^2 = 0.002 was comparable. However, when performing bimanual execution, the existence of an object revealed a significant difference between simple and complex tasks, F(1,39) = 31.88, p<0.001, η_p^2 = 0.450. Accordingly, bimanual movements that were complex and required object manipulation resulted in significantly lower average believability (mean = 5.60 $\pm$ 2.15) than other bimanual execution conditions (mean = 7.22 $\pm$ 2.03). The lower ratings in this condition were comparable with unimanual condition ratings (mean = 5.15 ± 2.36).

				Movement execution			
				Unimanual execution		Bimanual execution	
				Task complexity			
				Simple task	Complex task	Simple task	Complex task
Mirror size	Large mirror	Object manipulation	Without object	5.51 (2.28)	5.68 (2.22)	7.62 (2.07)	7.48 (1.91)
			With object	5.49 (2.51)	5.23 (2.42)	7.52 (1.99)	5.79 (2.26)
	Small mirror		Without object	4.98 (2.46)	4.87 (2.13)	6.88 (2.18)	6.72 (2.11)
			With object	4.93 (2.47)	4.48 (2.32)	7.07 (1.83)	5.39 (2.04)

Table 5.2 Mean (and standard error) values of believability

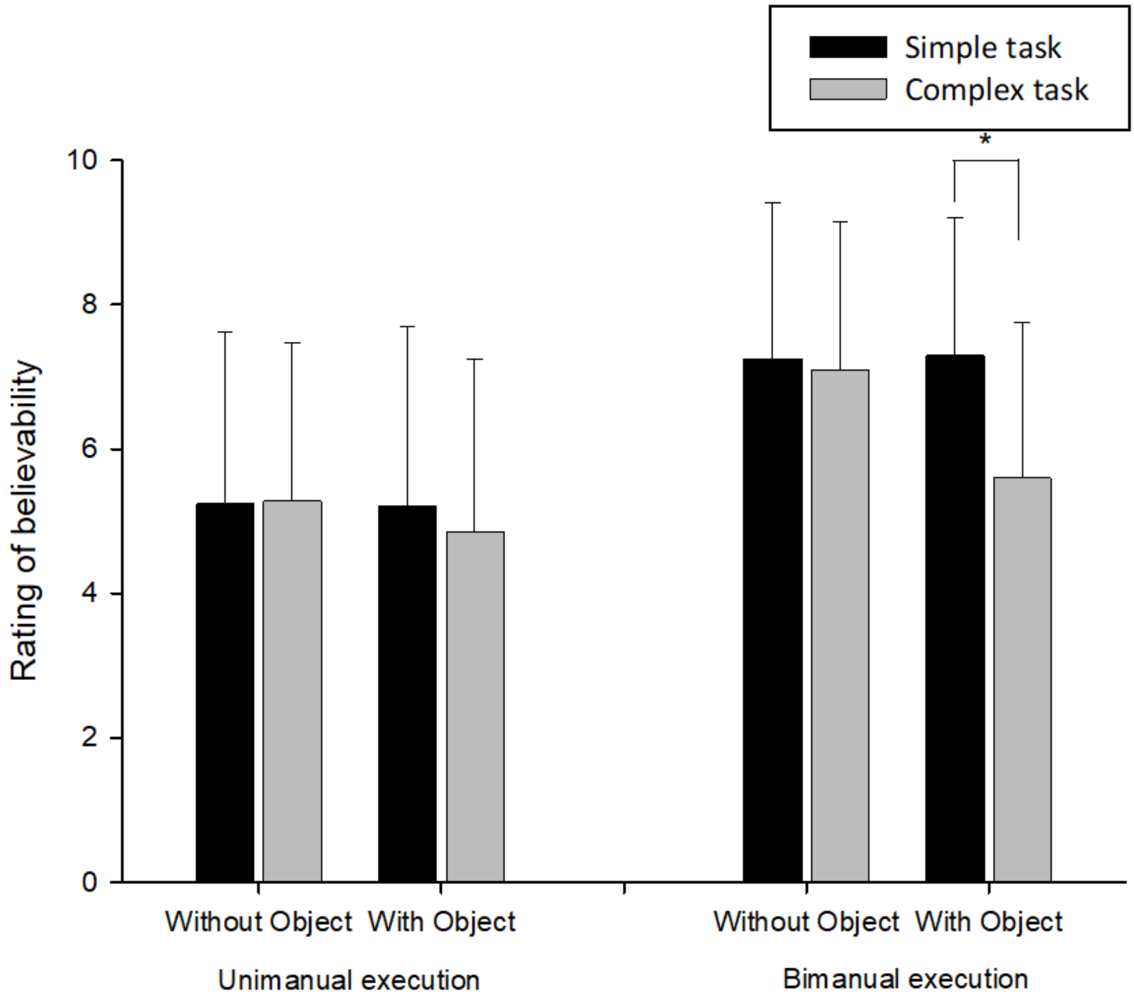


Figure 5.4 The result of three-way interactions (Movement execution [unimanual, bimanual] × Task complexity [simple, complex] × Object manipulation [with object, without object]). Across the experiment, bimanual execution had higher mean ratings of believability compared to unimanual execution. When tasks were executed unimanually, the mean believability ratings were comparable irrespective of the task complexity and the presence of object used in tasks. However, when tasks were bimanually executed, performing the complex task with object condition significantly decreased the mean ratings of believability.

Discussion

Decades of clinical research have demonstrated the effectiveness of mirror therapy in improving motor function of the hemiparetic limb in stroke survivors. However, the intervention is not applied consistently in studies, and the rationale for different approaches is not clear. The optimal protocol and whether this is the case for different patient groups is therefore uncertain.

Nevertheless, a recent meta-analysis revealed parameters that resulted in more effective outcomes in hemiparetic stroke. This study examined the impact of these parameters on the believability of the mirror illusion in unimpaired participants. Consistent with the meta-analysis, it was found that a large mirror elicited markedly higher ratings than when a small mirror was used. In contrast with the meta-analysis, bimanual movements generally elicited higher ratings. However, this study also found that ratings were modified by a combination of factors. For example, when unimpaired participants made bimanual movements involving the relatively complex manipulation of objects, the benefits of bimanual movements were lost. Below, these findings are addressed in turn and accounted for, along with what the implications for mirror therapy with stroke might be.

A post-hoc power analysis was performed to establish whether the experiment's sample size was sufficient. The effect of mirror size, movement execution, object manipulation, and task complexity on believability demonstrated 100% power, indicating that 40 participants were enough for the experiment. Three-way interaction between movement execution × Task complexity × Object manipulation, which drew particular interest, also showed 100% power.

The finding that a large mirror resulted in consistently enhanced believability ratings compared with when a small mirror was in place is consistent with the related enhanced effectiveness of mirror therapy demonstrated by the recent meta-analysis Morkisch et al. (2019). In line with providing what might be considered as a more immersive environment, Rowe (2019) highlights the opportunity afforded by a large mirror to integrate gross muscle movements into a task. In contrast, a small mirror may limit vision of the illusory limb, but also expose the hidden hand behind the mirror. These factors appear to modulate the quality of the visual illusion created by the mirror and also the effectiveness of mirror therapy. Several commercially available mirror boxes are small (comparable with the size of the small mirror in this study) offering a limited immersive experience. Instead, the hand is hidden inside the box so that the user may concentrate on their hand in the mirror. However, the enclosed nature of the box may also risk further sensory conflict due to the increased chance of sensory input to the unseen limb. For example, touching the material that makes up the box sides. Clinical experience suggests patients frequently bump up against the mirror box when moving in limited space available. When this happens, the patient typically pauses the intervention and relocates the position of the unseen hand. This implies that the illusion is disrupted by tactile information gained from touching the box.

In this study, the bimanual execution of movements resulted in generally enhanced believability ratings than those for unimanual movements. As is typical in mirror therapy studies where bimanual movements are employed, participants here made synchronous and symmetrical movements. For unimpaired participants, this clearly results in an experience where one receives visual feedback from the mirror that is congruent with the movements being made with the hidden hand. Under these circumstances where there is consistency between action and perception, it is perhaps not surprising that bimanual movements result in a more believable experience for participants. In contrast, unimanual movements uncouple action and perception.

While predicted, the finding of a more believable illusion when unimpaired participants made bimanual movements (generally at least) is in stark contrast with Morkisch et al.'s (2017) finding that unimanual movements (i.e. only moving the unimpaired limb) is a more effective approach than bimanual movements when mirror therapy is applied to individuals with stroke. Of course, the measures here are not the same (illusion believability in this study vs. motor improvement for the meta-analysis by Morskisch et al.), but the contrast remains marked. One might speculate that the relative congruence of the behavioural experience in both cases might explain these distinct findings. Where individuals have unimpaired movement, it seems clear that bimanual movements optimise the illusory experience. However, it was also found that making relatively complex movements and manipulating objects reduced this experience to the level of making unimanual movements. Therefore any factor that contributes to a lack of congruence between perception and action, even where this might be relatively minor, threatens the illusory experience. For patients with hemiparesis, it might be hypothesised that making bimanual movements provides no greater sense of congruence than making unilateral movements. Further, perhaps making bimanual movements also distracts patients from the therapeutic effects of observing the movement in the mirror. While the results of Morkisch et al.'s meta-analysis are unambiguous, it remains possible that the experience may vary for different patients and understanding these relationships more fully would justify further research.

As noted above, believability ratings in the present study for bimanual movements were modulated by task complexity and object manipulation. Previously, Rowe (2019) reported that as the complexity of a task (such as rotating cork balls) rises, the smooth performance of movements might be disrupted. In the present study, the task of rotating the cork balls was a difficult task, even to perform only with a hand in front of the mirror (unimanual). When instructed to rotate the cork balls bimanually, participants struggled to perform both hands at the same rate and occasionally dropped the cork ball. The fact that the movement is not smooth and that both hands are difficult to perform at the same rate can be attributed to the discrepancy between the illusory hand and the actual unseen hand. In this instance, the mismatch between action (predicted state) and perception (actual state) may have been more pronounced, reducing the sense of agency (Moore, 2016; Synofzik et al., 2008) (See Chapter 3).

Bimanual execution did not significantly differ when combined with one of the other parameters with lower believability (such as complex tasks, with object manipulation). However, a substantial decline in believability was seen when both parameters were used at once. The significant reduction in believability suggests that a threshold may exist depending on the relative difficulty of the task.

As alluded to above, in the case of patients with hemiparesis, even simple movements may be considered "complex" increasing conflict between perception and action; and, depending on the patients, it may simply be preferable trying not to move the hemiparetic limb. It may also be possible for the use of novel technology to provide a solution to overcome the discrepancy. Recently, the introduction of robotic gloves has been introduced to rehabilitation. Here, the patient could wear two gloves with the movements of the unimpaired limb being robotically mirrored by a glove worn on the impaired limb. In this scenario, it should be possible to create conditions where patients see and feel movements with their impaired limb that perfectly match those of the unimpaired limb. And while movement of the impaired limb may be passive, proprioceptive signals will still be produced, likely enhancing the perceptual experience.

Conclusion

In summary, this study examined the impact of combinations of mirror therapy parameters on believability in unimpaired individuals. Large mirrors elicited higher ratings than small mirrors, and bimanual execution elicited higher ratings than unimanual execution. The present study saw that there is a difference in believability depending on whether there is a discrepancy between the illusory and the unseen hand. However, when bimanual execution is combined with complex task and object manipulation, the believability ratings dropped as much as unimanual execution. This finding suggests that believability may decline with increasing relative task difficulty. Even simple tasks can be difficult for the hemiparetic hand, so it appears that in some cases, mirror therapy may benefit from not attempting to move the impaired limb. Perhaps the use of novel technology can be a solution to reduce the discrepancy between illusory and unseen limbs.

Chapter 6. General Discussion

Abstract

This thesis focused on examining the impact of mirror visual feedback (as applied in mirror therapy) on bimanual movements in unimpaired individuals and in stroke patients with hemiparesis. It also investigated the optimal conditions for optimising the visual illusion elicited by mirror visual feedback. In this final chapter, the results of the four experimental chapters are summarised, followed by discussion of the theoretical and clinical implications of the work. The chapter concludes by considering directions for future research that emerge from the work presented.

Summary of Findings from the thesis

The first experimental chapter of this thesis sought to investigate the movement of the hand behind the mirror (the *unseen* hand) while unimpaired participants performed continuous bimanual circle-drawing movements with mirror visual feedback (as in mirror therapy). The substantial positional drift of the unseen hand was observed, a finding not reported in previous studies of bimanual coordination with mirror visual feedback. The positional drift observed was most apparent when a visual template guiding movement was in place (Chapter 2, Experiment 1). It appeared that positional drift in these circumstances results from participants 'correcting' movements of the unseen hand in response to mirror visual feedback generated by seen hand movements.

Results presented in Chapter 2 gave rise to the notion that one might be able to examine an individual's *ownership* and *agency* over the illusory limb from moment to moment by identifying whether movements of the unseen limb were consistently modified in response to visual feedback created by the seen limb. A subsequent experiment and novel analytical approach in Chapter 3 addressed this issue. Accordingly, the movement of the unseen hand was analysed on a movement-by-movement basis using a repeating aiming task, revealing when corrective movements were consistent with feedback generated by the seen hand or not. Here again, comparable positional drift reported in the previous chapter was evident. However, by analysing the aiming movements of the unseen limb to targets predicted by the position of the seen limb, movement precision was comparable in all conditions (i.e. mirror and no mirror).

Nevertheless, in order to identify any movements of the unseen limb considered not to be consistent with illusory visual feedback, three criteria were identified in order to confidently characterise any such movements. By applying these, it was found that the unseen hand made aiming movements that did not follow the illusion at least once during any single trial, implying that sense of agency over the illusory hand was disrupted at times.

Chapter 4 applied the knowledge and techniques learned from the previous chapters in order to examine bimanual movements in a small number of stroke survivors with left hemiparesis. When the patients' affected limb was placed behind the mirror (i.e. was the unseen limb), movements were consistently hypometric in comparison to the control condition (i.e. no mirror). This finding was most pronounced in one case (a patient with spatial neglect) who also failed to move the affected limb at all in some trials when it was the unseen limb. Together, the findings presented in Chapter 4 suggest that mirror therapy may have the potential to reduce awareness in the affected limb when it is the unseen limb.

In Chapter 5 (final experiment), the impact of important mirror therapy parameters was examined on the perception (believability) of the illusory limb in unimpaired participants. According to a recent meta-analysis, mirror therapy for stroke patients is more successful when performed with a large mirror, only including unimanual movement (of the unaffected seen limb) without an object (Morkisch et al., 2019). Results presented in Chapter 5 consistently demonstrated that a large mirror elicited higher believability ratings than a small mirror. However, when it came to movement execution, bimanual movement received higher ratings than unimanual movement, in contrast to the finding of greater effectiveness in stroke patients when unimanual movements are instructed. However, when bimanual movement was performed with a complex task and included object manipulation, believability ratings were reduced to those for *unimanual* conditions. It is suggested that the primary contributory reason for the rating decline was the discrepancy (i.e. incongruence) between the illusory limb and other information (motor command, other sensory input). This study presented the parameters for optimising the visual illusion elicited by mirror visual feedback in unimpaired participants with implications suggested for achieving similar conditions for mirror therapy dsigned for stroke patients with hemiparesis.

Taken together, the experiments in this thesis explored the movement of the hand behind the mirror when individuals perform bimanual tasks with mirror visual feedback (as in mirror therapy). This work sheds light on the varying perception of the illusory limb and the knockon effects for action. These findings are now discussed by considering the theoretical and clinical implications along with directions for future research.

Theoretical implications

Positional drift

The substantial positional drift of the unseen hand was observed during continuous and discontinuous bimanual tasks with mirror visual feedback (Chapters 2,3, and 4). While the impact of mirror visual feedback has previously been shown to disrupt the reaching performance of the unseen limb (Holmes & Spence, 2005; Holmes et al., 2004), the robust and consistent findings here of very marked positional drift as a result of cumulative small errors have not previously been reported.

Positional drift indicates that visual capture of a limb (in a mirror) creates a powerful illusion which serves as a critical and dominating source of sensory input – apparently overriding any proprioceptive signals from highlighting the actual position of the limb (Holmes & Spence, 2005; Holmes et al., 2004). This provides evidence of how pervasive the visual illusion created can be and how it can be maintained in the face of marked discrepancies in the *seen* and *felt* position of the unseen limb. The drift of the unseen hand was caused by the accumulation of consecutive unseen hand corrections based on small errors in the seen hand, and the process underpinning the observed drift provided a basis to explore ownership and agency over the illusory limb.

Implicit measure for the sense of agency

Since the method of measuring the sense of agency by inferring the correlation of voluntary actions (implicit measure) (Moore, 2016) has been mainly approached with a temporal aspect (intentional binding) (Haggard et al., 2002), the spatial approach proposed in this thesis is novel. From a spatial point of view, a sense of agency during mirror visual feedback was observed depending on whether unseen limb movements were consistent with the illusory information or not. The predicted state and the actual state were compared based on the comparator model (Frith, 2005; Frith et al., 2000) to demonstrate how accurately the task was performed, and the sense of agency over the illusory limb was classified by including mirror visual feedback movement characteristics in the criteria (Synofzik et al., 2008). Although it is difficult to say whether the sense of agency is fully captured by taking this approach, this thesis provided a minimum guideline for the spatial implicit measure of the sense of agency that occurs during mirror visual feedback.

Interlimb coupling and the attentional hypothesis

The interlimb coupling that arises during mirror visual feedback may occur as a result of what has been proposed as the *attentional hypothesis* by Dohle et al. (2009). According to this account, it is thought the illusion of the unseen limb elicited by mirror visual feedback heightens spatial attention to the actual unseen limb (Dohle et al., 2009). During bimanual activities, attentional asymmetry has been shown to exist between the hands (Franz, 2004; Peters, 1981), but employing a mirror has been demonstrated to draw attention to the unseen hand and reduce the asymmetry (Franz & Packman, 2004; Metral et al., 2014). The spatial and temporal findings from our first experiment were consistent with the notion that the mirror enhances attention to the unseen limb.

However, the data presented in this thesis are not straightforward with regard to this issue. Perhaps most notably, it was found that spatial coupling was disrupted in hemiparetic stroke patients under mirror visual feedback conditions. Indeed, in the most extreme case, Patient 3 (see Chapter 4) sometimes failed to move their impaired limb when it was the unseen limb and when mirror visual feedback was in place. One might suggest that in the case of impairment in the unseen limb, illusory vision of the limb performing without impairment may reduce the attention (and effort) required to optimise related movement. If attentional deficits in the unseen limb during mirror visual feedback are consistently and extensively seen in stroke patients, the attentional hypothesis for mirror therapy may need to be revised.

Perhaps it would be preferable to interpret the attentional hypothesis in terms of greater *visual* attention to the illusory limb rather than proprioceptive attention to the actual unseen limb. Unimpaired individuals were unaware of the positional drift of the unseen hand caused by illusion (Chapters 2 and 3), and stroke patients were unaware of the presence of hypometria in movements of the unseen (affected) limb (Chapter 4).

A shift in attention to the illusory limb rather than the actual unseen limb may be associated with a more vivid illusion linked to the greater effectiveness of mirror therapy (Decety & Grèzes, 1999; Jeannerod, 2001). Findings here lend credence to the concept that mirror therapy will benefit from the internal simulation (Stevens & Stoykov, 2003). It was reported in Chapter 5 that the efficacy of mirror therapy may be altered by how the illusory limb is perceived. Perceiving that the hand in the mirror is *mine* (ownership) and under *my* control (agency) is likely to have the impact of enhancing the simulation of the affected hand's movement.

Clinical implications

Multiple studies over more than 20 years now have demonstrated the effectiveness of mirror therapy in improving movement and function in the hemiparetic limb following stroke (Thieme et al., 2018; Zeng et al., 2018). However, the precise details of how mirror therapy is implemented in different studies vary considerably with the result that guidance for practitioners wishing to use mirror therapy being vague (Rothgangel & Braun, 2013), likely reducing its use. A recent meta-analysis showed the effectiveness of mirror therapy depends on the specific parameters implemented (Morkisch et al., 2019). However, the authors of the meta-analysis do not provide any rationale for why the suggested parameters are optimal. This thesis provides support for the idea that the quality of the visual illusion elicited by any given setup may be critical to mirror therapy effectiveness. The more congruent the actual sensorimotor information involved is with illusory information, the greater the sense of embodiment of the illusory limb, leading to more effective mirror therapy.

Findings presented here (Chapter 5) suggest that the use of a large mirror, bimanual execution, a simple task, and the absence of an object are the factors that can maximise the illusion experience. While these parameters were shown to optimise the visual illusion in unimpaired individuals, a 'one size fits all' approach with regard to these parameters does not seem appropriate, given the heterogeneity of individuals with stroke.

However, regardless of the subject's condition, using a large mirror can be recommended in all protocols to enhance the immersive experience. Recent research findings and our findings both support the use of a large mirror, with the benefit of limiting additional incongruent visual information (actual unseen hand movement) provided in addition to the illusory limb. Although not mentioned in this thesis, Hadoush et al. (2013)'s study presented results that supported this viewpoint. They observed the effect of peripheral vision on illusion perception through a brain stimulation study, demonstrating that blocking the seen hand from vision can enhance the illusion experience. Perhaps using a large mirror to cover the actual unseen hand as well as blocking peripheral vision for the seen hand could be suggested as a way to enhance the illusion.

Away from mirror size, the remaining factors may need to be changed based on the patient's level of function. Given some stroke patients' limited movement, it appears that the complexity of the task or object manipulation should be adjusted based on the difficulty of the task perceived by the patient. Any task that generates a movement discrepancy between the illusory limb and the actual unseen limb appears to threaten the illusion, though the considerable drift observed in Chapters 2, 3 and 4 suggests for certain movements, there is some scope for incongruence without threatening the illusory experience (discussed in Chapter 5).

If it is difficult to reduce the discrepancy between the hands, unimanual movement rather than bimanual movement should perhaps be recommended for mirror therapy (as suggested by (Morkisch et al. (2019)).

Perhaps an additional complexity here is the nature of the motor deficit characterising individual stroke survivors. While hemiparesis (weakness in the affected limb) is common following stroke, patients also typically present with a component of *'learned paralysis(nonuse)'* (Ramachandran, 1994). The term "learned paralysis" refers to pseudo-paralysis that persists despite recovery from temporary inhibition or compression of normal tracts and cells, and the main effect of mirror therapy appears to be to recover this (Ramachandran & Altschuler, 2009; Ramachandran & Rogers-Ramachandran, 2019). However, more primary motor deficits may be outside the influence of mirror therapy and may act as a factor that still causes a discrepancy between the hands.

Findings in this thesis (Chapter 4) show that some stroke patients with no discrepancy during bilateral movements may produce relatively hypometric movements with the unseen affected hand under mirror visual feedback condition (cf. motor extinction, (Heilman, 2004 #5281)(Punt et al., 2013)) and are unaware of this. It is unclear what the optimal approach to mirror therapy might be in such cases.

Directions for future research

This thesis reports the results of experiments that examined movements of a small number of individuals with stroke (n=3). Given the findings, the uncertainty as to the generalisation of these and the heterogeneity of stroke patients, a larger study would be welcome. Such a study should aim to investigate movements of the unseen (affected) hand in hemiparetic stroke and pay attention to the differences inherent in the population; a 'one size fits all' approach is unlikely to be optimal. In addition, since there are still questions about the intensity and duration of the mirror therapy (Michielsen et al., 2011), studies would be welcome that investigate hand movements that arise when mirror visual input is experienced for a longer period of time.

In this thesis, a novel analysis systematically evaluated the sense of agency over the illusory limb during mirror visual feedback, demonstrating that this can be crucial to the optimal illusion experience and likely the effectiveness of mirror therapy. Further investigation that combines such findings with brain imaging would strengthen this relationship further. Hadoush et al. (2013) research showed the potential to do this. They revealed that a more immersive visual illusion during mirror visual feedback facilitated ipsilateral primary motor cortex activation using magnetoencephalography. If an illusion break is detected during the trial using novel analysis, it is likely to appear as a decrease in activation in the ipsilateral primary motor cortex.

Conclusion

Mirror therapy following stroke typically involves patients making symmetrical bimanual movements with a mirror placed in their mid-sagittal plane. The patient's vision is directed to the reflective surface of the mirror, while the movement of the unimpaired (seen) limb generates an illusory limb that appears to move normally in the same perceived spatial location as the affected (unseen) limb. While mirror therapy is known to be effective in improving movement and function in the hemiparetic limb, the processes that underpin this effectiveness remain uncertain. Surprisingly, given the aim of mirror therapy, there are no previous studies that have examined the immediate impact of making bimanual movements during mirror visual feedback on the performance of the affected (unseen limb). Within this context, the thesis here examined the impact of mirror visual feedback on bimanual coordination, first in unimpaired participants and subsequently in a small number of individuals with hemiparetic stroke. Results were supportive of mirror visual feedback creating a powerful illusion. Indeed, by carefully measuring the movements of both limbs, it was possible to observe how visual control of the unseen limb was based on illusory information. A major contribution of this thesis was demonstrating how one could infer agency of the illusory limb by examining these movements; and while such agency tended to prevail, it was also possible to identify occasions where this was lost. A similar study with stroke patients showed how movements of the affected (unseen) limb appeared to be disrupted by mirror visual feedback and how such feedback may reduce awareness of the affected limb in some patients, contrary to some previous reports. Finally, the thesis addressed what the optimal parameters are for mirror visual feedback in order to create the most believable visual illusion; and while some findings were consistent with those from a recent meta-analysis addressing mirror therapy effectiveness, others suggested caution and a more nuanced picture. Together, the findings in this thesis have shed light on how mirror visual feedback (as provided by mirror therapy) modulates motor behaviour and how studying such behaviour can help to identify the optimal conditions for practice.

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