BEHAVIOURAL INVESTIGATIONS OF INTERPERSONAL ACTION

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A thesis submitted to
The University of Birmingham
For the degree of
DOCTOR OF PHILOSOPHY

School of Psychology
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The University of Birmingham
February 2012

ABSTRACT

Many everyday motor tasks require interpersonal action where the goal of the joint task is shared among all those involved. The aim of this thesis was two-fold; first, to explore bottom-up and top-down factors affecting interpersonal movement and second, to examine discrepancies in motor strategy arising between intrapersonal and interpersonal task conditions. In Chapter 2, participants coordinated their wrist movements to a live model whose own actions increased in frequency over time. Motoric and spatial contributions to the stability of interpersonal coordination were teased apart; testing whether spatial congruency overrides anatomical congruency. However, both factors influenced the task. Furthermore, the representation strength of these factors was not influenced by perspective (allocentric, egocentric). Chapter 3 investigated synchronization to self-versus-other when agency was either unknown or when participants were told (correctly or falsely) who they were synchronizing to. Participants synchronized arm movements to point-light stimuli derived from either their own or another person's previous motion recordings. Performance during self-belief trials was better relative to other-belief trials, indicating a significant top-down modulation of behaviour. Chapter 4 probed interpersonal adherence to Fitts' Law, specifically looking at how task workload was shared across players when efficiency was emphasized. Players placed targets down at location distances of their discretion in order for their task partner to hit them. An equity-efficiency trade-off which violated Fitts' Law was observed. Chapter 5 studied how motor strategy across intrapersonal and interpersonal conditions differed in a reach-to-target task where two vBOTs jointly controlled the movement of a single cursor. Force perturbations ensured that both participants/hands experienced one shared 'difficult' direction and one shared 'easy' direction; the other two directions were difficult for one and easy for the other. Interpersonal behaviour was characterized by an equity-efficiency trade-off absent in the intrapersonal task. Overall, this thesis provides behavioural evidence of how interpersonal motor behaviour is modulated by bottom-up, top-down, social-goal and movement-control variables.

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank all those who have helped me over the course of my PhD. Firstly, thank you to the MRC and ESRC for sponsoring my studies. Secondly, huge thanks must go to my supervisors, Chris Miall and Kim Quinn. I am extremely grateful for all the support and guidance you have both given me. Thanks also to the past (esp. Neil, Carl) and present members of the PRISM lab, above all the two Jonathans.

Jonathan Winter: You have been a never-ending source of help from day one! Thank you for willingness to always lend a hand and for going well beyond the call of duty.

Jon Kennedy: Thank you for all your help, kindness and patience. I must in particular acknowledge all the invaluable mathematical assistance you provided me in relation to Chapter 4. You are an all-too-modest genius!

Chapter 3 was a collaborative project with Juliane Honisch, who I wish to also thank. It has been a pleasure working with you and I wish you great success in your future.

I am also indebted to the long-time friendships of fellow students Nicola(!), Vera, Si & Aimee. Thanks also to Denise for all her support. You have helped to keep me laughing during my postgraduate years. Thanks also to my old friends Noura and Mariam. In addition, I'd also like to thank my brothers, Conrad and James.

Finally, and most importantly, I wish to thank my parents Michael and Antoniêta, who I love deeply. I appreciate all the opportunities you have given me, support you have shown me and care you have taken with me. I would not have been able to get this far without you. Thank you for everything you have done for me.

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 Introduction

Whilst many of life's daily activities are performed individually, there are also countless tasks that simply cannot be performed in isolation, and that instead require two or more agents to act together to achieve a common goal. Such tasks might be infeasible or merely too physically demanding to be performed alone, as for instance in transporting heavy furniture, or they might be motivated by more social concerns, such as cooperating in an ensemble musical performance or even engaging in competitive interaction during a game of sport.

From a survival point of view, interpersonal actions such as those presently illustrated have enormous ecological value in allowing the individual to achieve otherwise difficult, if not impossible goals, whilst potentially also fostering social well-being through allowing interaction with others. For clarity, interpersonal action is loosely defined here as any action undertaken by two or more individuals, usually with a shared though not always conscious objective. Co-actors might engage in identical, complementary or completely dissimilar actions, which might be performed in unison or with a degree of spatial and/or temporal separation. The aim of this thesis was to address a fundamental question in any study of interpersonal action, that is, how might the action of one agent influence the motor responses of another agent when both parties are engaged in a joint task?

On the surface it seems obvious that people must be capable of taking into account the actions of others, so that when performing with another person, the joint goal or at least one's own contribution to that joint goal is accomplished and done so in what is presumably a fairly optimal way. So, for example, when an error is observed in one task partner's action, the other player might be able to compensate for it in their own movement. However, in an interpersonal context, the mechanism governing such a process is far from evident, as both parties share neither brains nor bodies. Undoubtedly, an early stage in any such process would require the ability to perceive the actions others perform and later stages might involve comprehending the intent associated with the action, which might aid prediction of future actions. The study of the motor system has provided some plausible answers to these questions. In particular, the relatively recent discovery some 20 years ago of so-called 'mirror neurons' in the monkey brain is believed by many to offer a neural substrate for understanding and predicting other's actions, as well as providing a means to account for observational learning through imitation.

The motor system and specifically mirror neurons, represented a recurring theme throughout this thesis and hence an overview of some of the principle findings in both these areas is warranted here. Following this discussion, this general introduction chapter will conclude with a summary of the objectives of the four experimental chapters that formed the core of this thesis.

1.1.1 The Mirror Neuron System

Mirror neurons are neurons which fire both during the observation as well as the execution of action (for a review, see Rizzolatti & Craighero, 2004). Their discovery in the ventral premotor cortex (area F5) of macaques was serendipitous in that the original aims of the experiment had been to extend previous single-cell data on neurons in area F5 with a new more fine-grained examination whilst the macaque performed a series of grasping actions directed towards different objects (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992). Previously reported were canonical neurons whose firing was tuned to the visual presentation of objects requiring a specific grasp type (e.g. precision or whole hand grip) and also motor neurons that fired when the animal performed a particular object-orientated action. During the course of this latest exploratory investigation, however, it was noted that some of the neurons within area F5 possessed previously unreported and quite unexpected firing properties. Specifically, they discharged not only when the macaque executed a goal-directed action, such as grasping a food item, but also when the macaque merely observed this same action being performed by another macaque or human. In contrast to canonical neurons, which discharged during the observation of the object presented in isolation, these mirror neurons expressly required the interaction of the agent with the object, confirming the significance of goal-directed action in mediating their response pattern.

Gallese, Fadiga, Fogassi and Rizzolatti (1996) later conducted an even more comprehensive examination of the firing properties and the relative distribution of mirror neurons in F5. Whilst some neurons showed generalized activation to movements of different class (placing or grasping), others appeared much more specialized, with firing tuned even to the level of specific grasp type. Moreover, whilst the majority of mirror neurons exhibited firing in response to actions which preserved the goal of the movement, though not necessarily the means of producing it, some 'highly congruent' mirror neurons required a strict match between the goal and the means to achieve the goal. For instance, only a specific grasp type acting on a given object would trigger activity. Hand or mouth manipulation of objects were noted to be the most successful at inducing mirror neuron activity, whilst actions involving tool use or emotive gestures were mostly ineffective. Furthermore, intransitive actions that were not orientated towards an object, such as grasping an imaginary ball, failed to trigger the same strength of response when compared with the equivalent goal-directed action. This highlighted once again the importance of the interaction between the agent and the object. Finally, to negate the suggestion that mirror neuron activity during action execution was simply the result of observing one's own performance, macaques were tested under conditions devoid of illumination. Nevertheless these neurons continued to fire, providing evidence that the motor signature evoked during execution likely does play a role in driving the activity observed during active execution.

Going one step further, Umiltà et al. (2001) revealed that a subset of grasping mirror neurons responded even when the supposedly critical part of the action (i.e. the interaction between the agent and object) was hidden from view by a screen. However, this only held true when the monkey had seen both the object before it was concealed from view (and hence could infer its presence) and also the hand as it disappeared behind the screen. Observing the placing of an object behind the screen alone was ineffective at driving a response. Crucially, neuronal activity was temporally correlated with the agent-object interaction and thus did not simply represent sustained firing following the initial presentation of the object. This ruled out the argument that firing could be due to the object simply being retained in memory. As a whole, the results led to the suggestion that mirror neurons might be the neural substrate for action recognition and potentially also action understanding, as even when visual information was incomplete, the monkey appeared able to construct internally a representation of what they had seen. To put it another way, despite the information lost when movement was hidden behind the screen, recognition of the goal of the action was preserved. This enabled the action as a whole to be coded and mapped onto the monkey's own motor system as though they had themselves performed it. It is this 'playback' of an observed action in the perceiver's own motor system that purportedly permits action recognition and is hypothesized as a neural mechanism for understanding and predicting the actions and intents of other agents.

In addition to the mirror neurons reported in F5, neurons with similar properties have been found in the posterior parietal cortex (PF or BA7b) of the macaque (Fogassi et al., 2005; Gallese, Fadiga, Fogassi, & Rizzolatti, 2002). Up until this point, this chapter has reviewed mirror neurons in the brain of lower primates. However, since their discovery, it has been posited that neurons with similar properties may operate in humans.

As yet there is only one recent study providing the first direct evidence via single-cell recordings of mirror neurons in the human brain. This study is founded on recordings from 1177 cells in the medial frontal cortex and medial temporal cortex of 21 patients undergoing treatment for epilepsy (Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010). Patients observed and performed grasping actions and emotional facial expressions whilst cell activity was recorded from the supplementary motor area (SMA), the anterior cingulate cortex (ACC) and medial temporal lobe structures, including the hippocampus and amygdala. Four cell types were identified: those that responded to the observation of an action alone, those that responded to the execution of an action alone, those that responded to both action and observation but of different actions (e.g. responded to a smile observation and a frown execution) and finally those that responded to both action and execution of the same action (e.g. responded to a matching smile observation and execution). This final class of observation-execution 'matching' neurons indicate that neurons with mirroring properties resembling those previously reported in primates, also occur in the human brain where they respond both to the observation and execution of grasping actions and facial expressions. Of the brain regions tested, such mirror neurons were found to be significantly distributed within the SMA and hippocampal regions in the medial temporal lobe: areas generally established as dealing with action preparation and memory, respectively.

Unfortunately, on clinical grounds, the human analogue for F5 in primates, Broca's area, could not be investigated. Broca's area is known to be a region critical to speech production, but it has been suggested that it may also play a role in the sensorimotor integration of external information about biological movement with the internal motor representations of those observed actions (Binkofski & Buccino, 2004). Moreover, the actions executed and observed were quite different from the monkey studies, including social actions such as smiling. The neurons in the human study were, therefore, both spatially and functionally different from those examined in primates, providing support for a wider mirror neuron system distributed across the human brain, with different areas contributing different information about the action (Mukamel et al., 2010). These last researchers further suggest that the mirror neuron activity seen in the medial temporal region during action observation could represent reactivation of a stored memory, which matches the observed action. On the other hand, activity seen during execution might reflect the actual formation or updating of a memory trace itself.

Furthermore, whilst the ability to assimilate the representations of other's actions onto one's own motor system may be key to allowing, for example observational learning, it does pose new questions such as how the motor system discriminates between self and other. Mukamel et al. (2010) point out that a subset of neurons tested responded with reverse patterns of excitation and inhibition during executed (self-generated) and observed (externally-generated) actions. They add that firing properties such as these might provide a means of self–other discrimination, allowing the sense of agency (ownership) of the action to be achieved, whilst also allowing behaviour to be regulated so that, for instance, imitation is only performed when appropriate rather than all of the time. To conclude, although this first report provides promising evidence for the existence of mirror neurons in humans, a more detailed single-cell examination is still needed to describe more fully their firing properties and also possibly to test new sites.

In addition to this recent direct evidence for mirror neurons in humans, there already exists an increasing body of indirect evidence in the form of behavioural and neuroimaging research (for a review, see Rizzolatti & Craighero, 2004). Some early behavioural evidence supporting the occurrence of mirror neurons in humans was provided by Fadiga, Fogassi, Pavesi and Rizzolatti (1995). They recorded motor evoked potentials (MEPs) from the hand muscles of participants who underwent transcranial magnetic stimulation (TMS) over their left motor cortex whilst either observing an action (i.e. the experimenter grasping objects or tracing geometric figures in the air with their arm). Recordings were also taken whilst participants observed an object alone or whilst they merely detected the dimming of a light stimulus. It was hypothesized that if observed and executed actions were indeed co-represented in a human mirror system, then TMS over the left motor cortex should manifest in larger MEPs in the contralateral right hand during action observation compared to object observation. Since observing an action should already activate the motor system, less excitation should be required to evoke a MEP and hence for the same level of stimulus, the MEPs elicited should be larger. Indeed, the authors did find enhancement of MEPs during action observation, but more specifically the precise pattern of MEPs was linked to the muscles involved in the actual execution of a given movement. In other words, only the excitability of muscles that would be involved in performing the observed action were modulated, whilst activity in other muscles remained unchanged. No such MEP enhancement was reported for mere object observation or during the more cognitively demanding light-dimming detection task.

In a later study, Maeda, Kleiner-Fisman and Pascual-Leone (2002) also measured MEPs induced by TMS, whilst participants watched videos of different types of intransitive finger movements, which were presented to the participant from either a natural egocentric (facing outwards) or unnatural allocentric (facing towards) vantage point. They confirmed the results of Fadiga et al. (1995), showing that the facilitation of the MEP response was specific to those muscles that were used in the finger movement observed. Force transducers measuring the finger movements elicited during TMS also revealed that when observing up or down finger movements, the participant's own finger moved more vertically, whereas when observing side-to-side finger movements, more horizontal finger movement was evoked. This strongly suggests that upon observing an action, motor output to the muscles actually involved in that action is boosted such that execution of the observed action is primed. Nonetheless, MEPs were found to be greatest when the orientation of the hand in the video matched that of the participant compared to when the hand was viewed from an allocentric perspective. Taken altogether, these results reveal how observed actions 'resonate' within the motor system of the perceiver and the strength of this resonance may be influenced by factors such as the orientation of the observed action relative to the observer.

1.1.2 Shared Representations for Action and Perception

Following on from the idea that observing an action may prime the execution of that action, some researchers have proposed that there is a shared representation or 'common code' for perception and action (see Prinz, 1997). Much of the supporting evidence for this theory comes from reaction-time tasks where participants must choose the correct motor response in reaction to a given stimuli, and from kinematic data obtained from interference paradigms where participants execute movements whilst simultaneously observing either congruent or incongruent movements made by other agents. For instance, it is known that when responding to stimuli in a choice reaction-time task, it is easier to respond when the spatial arrangement of the stimuli matches the spatial arrangement of the correct response button compared to when it does not; this is known as stimulus-response compatibility (SRC) effect. Brass, Bekkering and Prinz (2001) examined the degree to which motor similarity as well as spatial similarity influences response times. Their participants performed finger responses in reaction to the movement onset of a finger lifting (up) or tapping (down) displayed onscreen.

Participants were faster to respond when their motor response was congruent to the action they had observed, and this held true even when spatial compatibility was taking into account by having the videos played upside down. Observing congruent actions, therefore, primed the execution of action by way of motor as well as spatial similarity, supporting the idea of a shared representation for action and perception in the motor system, possibly located within the mirror neuron network.

Although related to motor priming tasks, interference paradigms usually investigate the kinematic consequences of observing and executing actions performed simultaneously. These studies draw on the 'interference hypothesis', which states that because action and perception have a shared representation, when this common code is already in use during perception, it cannot also be (fully) functional during action planning and control, and vice versa (Prinz, 1997). Indeed, interference effects from the observation of incongruent actions are not limited to response initiation but also are evident in continuous movement. Kilner, Paulignan and Blakemore (2003), for example, demonstrated that participants who viewed movements that were incongruent (orthogonal) to their own concurrently executed action, showed much more variability in the output of their movement as measured by movement in the direction orthogonal to intended movement. Greater variability during incongruent conditions hinted that participants incorporated aspects of the observed movement into their own movement trajectory. This type of interference to motor output has been termed 'motor contagion' (Blakemore & Frith, 2005). Thus whether in slowing down response initiation during motor priming tasks or increasing the variability of executed action during simultaneous action observation, these interference effects have all implicated the activity of mirror neurons as their source.

Blakemore and Frith (2005) noted that motor contagion arises even for intransitive movements in humans (e.g. Kilner et al., 2003) and thus mirror neurons in humans must be distinguished from those in monkeys, which characteristically only increase activation in response to goal-directed action (di Pellegrino et al., 1992; Gallese et al., 1996). Blakemore and Frith concluded that mirror neurons are likely to be only one part of a wider mirror network, which comprises a minimum of three levels. They hypothesized that the first level of this network would be where motor contagion from observing biological agents occurs. The second level they suggested would house the actual mirror neurons responsible for representing goal-directed action, whilst the final level would ultimately allow the intentions of others to be represented or 'mirrored' within the system. This is supported by evidence demonstrating that children choose different imitation strategies based on whether they interpret a movement as an goal-orientated action or not (Wohlschläger, Gattis, & Bekkering, 2003).

In addition to the behavioural research already mentioned, neuroimaging techniques such as functional magnetic resonance imaging (fMRI) have provided a non-invasive way of shedding light on the neural correlates of 'mirroring' in humans. The key areas implicated in the human mirror neuron system are the ventral premotor and parietal cortices, specifically the rostral part of the inferior parietal lobule and the lower part of the precentral gyrus together with the posterior part of the inferior frontal gyrus (IFG) (Rizzolatti & Craighero, 2004). Buccino et al. (2001) used fMRI to investigate whether the observation of video clips of transitive (object-directed action) and intransitive actions (pantomimed action) made by different effectors would lead to somatotopically organized activation of the premotor cortex. They showed that as the observed effector changed from mouth to hand to foot, the activations in the premotor cortex also shifted in location from ventral to dorsal, respectively, in line with the representation of the analogous body part in the homunculus. Their results, therefore, demonstrated that the observation of an action does indeed recruit the same specific neural areas that would usually be involved in the performance of the action and this was true for both transitive and intransitive observation conditions. Transitive actions also activated both parietal lobe and frontal regions of the mirror-neuron system, whilst intransitive actions activated only frontal regions, suggesting that these two action categories may dissociate somewhat. Nevertheless, participants seemed capable of mapping an observed action onto their own motor system even when these actions were not directed at an object. This contrasts with the macaque-related research, which has failed to show mirroring activity in response to intransitive actions and strongly implies that the human mirroring system may be more developed than that of primates.

More recently, there is evidence that the activity of the parieto-premotor mirror system in humans during action observation reflects the underlying motor expertise of the individual. Calvo-Merino, Glaser, Grèzes, Passingham and Haggard (2005) showed that compared to non-expert controls, when experts in ballet or capoeira were shown video clips of their own dance style, activations were far greater than when they observed the other style. Activations were found bilaterally in the premotor cortex and the intraparietal sulcus as well as in the right superior parietal lobe and left posterior superior temporal sulcus. Activity in these areas was heightened for ballet dancers when they watched ballet videos relative to capoeira videos and vice versa for capoeira experts. The unskilled controls showed no such differences across either dance style. This pattern of result revealed that although action observation across all conditions was sufficient to activate the mirror network, visual kinematics alone could not explain the level of neural activity, which seemed instead to be modulated by the motor repertoire of the individual. Thus, when observing an action which is already well learnt, the representation of the action will 'resonate' much more strongly within the neural system. The degree of motor resonance within this shared representation network is hence governed not only by perceptual information but also by sensorimotor experience.

1.1.3 Internal Models in Motor Control

In order to interact with one's environmental surroundings, let alone the other agents inhabiting it, it is necessary for an individual to be in control of their movements. For this reason, understanding how the motor system operates within an individual may provide clues for how the same system copes with representing, interpreting and engaging with the actions of others.

The motor system can be likened to a loop in which a motor command (e.g. “pick up a cup”) is transmitted to the appropriate muscles so as to bring about a change in the body state. Information about this transformation and, specifically, the sensory consequences of the command are relayed back to the motor system by way of sensorimotor feedback. This feedback updates the motor system with details about the new body configuration (e.g. joint angles) whilst also providing information about the environmental surroundings, all of which can be borne in mind when computing future action commands, and hence closing the loop. The (outcome of the) body state cannot be directly accessed and instead can only be provided by feedback information. For example, just before picking up an object, visual information can be used to estimate the object's mass, based on similar past encounters. However, this prediction can only be confirmed as 'correct' through actual manipulation of the object (sensory feedback).

Wolpert, Doya and Kawato (2003) have proposed that an analogous 'social interaction loop' may operate whereby the motor commands of one person give rise to a communicative input signal, which modulates the perceiver's mental state and subsequent behaviour. This behaviour then provides feedback to the original agent, allowing them the opportunity to update the next motor command and thereby, completing the loop. This type of loop requires that the state of others, including their internal mental state, can be estimated in much the same way as one's own bodily state. Thus through prior encounters, a model of another person's responses to one's own actions can be predicted. The computations involved in the control of one's own limb movement may not be intrinsically dissimilar to those involved in social interaction, although clearly any control issues inherent to the sensorimotor loop are only magnified in the more complex social variant of the loop (Wolpert et al., 2003).

The brain is thought to internally represent the different stages involved in the sensorimotor loop through implementing internal models (Miall & Wolpert, 1996). Two types of internal model are thought to operate in the central nervous system: forward and inverse models. Whereas forward models predict the outcome of the motor command, inverse models predict the motor command required to achieve a given outcome. The forward model receives a copy of the motor command known as an efference copy and combines it with information about the current body state and external environment to build a prediction of the consequences of a given action. This prediction can then be compared against the actual consequences of the action and a prediction error generated for use in improving future predictions. In the social interaction loop, the forward model would predict the responses of one agent to another agent's motor command (or perceived action). Hence the computations involving the social and sensorimotor loops may be operationally rather similar (Wolpert et al., 2003).

Haruno, Wolpert and Kawato (2001) put forth the MOSAIC computational model where forward models are paired with inverse models into controller-predictor modules. For a given action such as lifting a box, the efference copy of the motor command would be sent to several different forward models, which predict the context in which movement occurs.

One model might predict the sensorimotor consequences associated with an easy lift (box empty), whilst another would do the same for a difficult lift (box weighted). The actual feedback received would then enable the model to compute which of the two contexts was most likely correct. Weightings could then be adjusted so that the inverse model associated with the forward model that best predicted the context would be used to generate future motor commands when presented with a similar situation. Wolpert et al. (2003) have since proposed a extended hierarchical version of the model, HMOSAIC, which comprises several layers allowing bottom-up and top-down control of movement. The lowest level is essentially the previously described MOSAIC model, where paired forward and inverse model units concern themselves with the prediction and control of the low level dynamics of elementary movements based on different contexts or states. This information propagates up to a second mid-level representation where the temporal sequencing of elementary movements is characterized and where actions are possibly encoded independently of the effector used.

Beyond this, the highest levels in the model would allow for abstract representation such as processing the goals and intentions associated with an action. Wolpert et al. (2003) explain that for imitation, for example, the individual would predict the model at the various levels of the HMOSAIC that would be required to produce the observed behaviour. Ultimately one's own HMOSAIC might be used to estimate the hidden states of others in much the same way as it predicts the state of one's own system. Finally, it is the action coding present in the intermediate tier of the HMOSAIC that has been suggested as a candidate level for where mirror neurons might function (Miall, 2003).

1.2 Overview of Experimental Chapters

The research summarized above indicates that there is an interaction between neural systems engaged in action execution and action observation, modulated by knowledge of actions goals.

The experiments described in this thesis were conducted as research into the role that these bottom-up and top-down influences play in mediating interpersonal action. Interpersonal action in this context refers to actions carried out by two or more individuals, usually with a shared, though often implicit, goal in mind. Specifically, the thesis concerned itself with how the experience of observing or engaging with the action of one agent might have an impact on the subsequent or concurrent actions of another task partner when both parties were performing in some common motor-based task with a shared goal. Additionally, this thesis examined how individuals strategized their contribution to a joint motor task so as to optimize interpersonal performance. This involved investigating how labour was partitioned differently across individual and interpersonal performance.

To carry out these studies, a series of behavioural experiments were performed and multiple testing methods were employed. The methodologies selected for each study were chosen on the basis of their appropriateness in acquiring data to directly aid the testing of each study's principle hypotheses. By using a wide range of methods to inform the study of interpersonal action, it was anticipated that a preliminary overview of the behavioural implications of such action would be provided at a fairly broad level, whilst perhaps also hinting at which methodological avenues might be more productive to pursue the field in future work.

In Chapter 2, the hypothesis that action observation and execution were represented in an egocentric, action based coordinate system was tested. Motion tracking was used to investigate the degree to which spatial (i.e. perceptual) and motoric (i.e. sensorimotor) congruency affects the coordination stability between a blindfolded model and a participant simultaneously performing oscillating hand actions. Different starting hand configurations manipulated the examined congruency variables. Movement pace was set by the model wearing headphones playing the beat of a metronome that gradually increased in tempo making the task increasingly difficult. Stability was measured by the length of time participants were able to keep to the original coordination configuration they had begun with at the start of the trial. The model was positioned at either an allocentric (face-to-face) or pseudo-egocentric (side-by-side) viewpoint relative to the participant. Therefore, the aim was to test the separate contributions of perceptual and motor involvement in interpersonal coordination stability, by independently manipulating congruency between model and observer along these two dimensions. Also assessed was the influence that viewing perspective played in modulating such contributions.

Chapter 3 examined the hypothesis that both bottom-up (i.e. the degree of perceptual and motor match in the motor system for self versus other representations) and top-down (agency-belief) information play a role in modulating interpersonal synchronization. Performance was relative to point-light stimuli of an agent executing a repetitive arm movement. Motion capture was again used, this time to record synchronization performance which was investigated through asynchronies and other related synchronization measures. Stimuli were derived from recordings taken from the same participant (self) or another person (other). Information surrounding the identity of the stimulus agent was sometimes withheld completely, sometimes given accurately, and sometimes was deceptive in nature. It was anticipated that the observation of self-generated actions or actions perceived as self-generated would improve performance relative to actions generated by another agent.

Chapter 4 examined adherence to Fitts' Law (Fitts, 1954) in a two-person version of a classic target-hitting task. The hypothesis was tested that when under instructions to work together to optimize task speed and accuracy, participants would perform so as to reduce the index of difficulty experienced by their task partner. Specifically, it was anticipated this would involve placing more difficult targets closer to one's action partner in order to make their aiming movement easier. Amplitudes between targets and target sizes themselves were varied to create different indices of difficulty (ID), whilst capacitive button sensors recorded movement times (known to be a function of ID) and motion capture tracked amplitude measurements. To give participants experience of the effect of changing ID, prior to interpersonal performance all participants were tested individually.

Finally, in Chapter 5, position and velocity data were collected from two force-generating robotic manipulanda (vBOTs; cf. Jackson & Miall, 2008) during a novel reach-to-target task performed either bimanually or interpersonally with a common goal to perform efficiently. The hypothesis explored was that participants would learn to predict, based on their own prior isolated experience of the task and the within-trial information available to them, which directions were easy or difficult for their interpersonal actions and thus alter their relative contribution to the task accordingly. The vBOTs jointly controlled the movement of a single onscreen cursor towards four possible target locations. Force perturbations acted on the vBOT handle so that both participants/hands experienced one shared 'difficult' (perturbed) direction and one shared 'easy' (unperturbed) direction; the other two directions were difficult for one and easy for the other. The purpose of this experiment was to probe how participants would distribute their contribution to the task so as to optimize overall speed and accuracy when the difficulty of their task partner could only be inferred from the visual cursor display. Specifically, as efficient cooperative actions were emphasized as the goal, it was anticipated that, for example, the participant/hand in the 'easy' condition should generate more of the shared cursor movement when their partner/other hand was in a 'difficult' condition.

Taken altogether the work carried out across the experimental chapters represented an effort to address the core question of this thesis, that is, how one person's motor actions may influence the subsequent characteristics (e.g. kinematics) of and/or choice of actions (e.g. strategy) executed by another agent performing alongside them, so as to optimize some measure of performance such as speed or synchronization. Typically, the studies described in this thesis suppose that knowledge of one's own movements under specific conditions might be employed as a template for understanding and engaging with the actions of others. Consequently, participants were often given prior isolated experience of a task before they performed interpersonally (Chapters 4 & 5). Another related interest of the thesis was to dissociate the influence of bottom-up and top-down effects on interpersonal performance. To test bottom-up effects, interpersonal movements were manipulated across the dimensions of spatial and motoric similarity (Chapter 2), whilst top-down information surrounding agent identity was manipulated to explore the contribution of this source of top-down information to interpersonal behaviour (Chapter 3).

CHAPTER TWO

INDEPENDENT INVESTIGATION OF THE SPATIAL AND MOTORIC CONTRIBUTIONS TO PHASE STATE STABILITY DURING INTERPERSONAL LIMB COORDINATION

2.1 Introduction

Previous research had already demonstrated that as the frequency of oscillation increases a parallel mode of oscillation tends to spontaneously switch to the more stable symmetric mode, but that the opposite does not occur (Kelso, 1984). This was purported to be due to activation of homologous muscles; however, Mechsner, Kerzel, Knoblich and Prinz (2001) revealed that in simply inverting one hand during a bimanual finger oscillation (resulting in spatially parallel rather than spatially symmetric oscillation patterns now activating homologous muscles), the symmetric oscillation mode became more stable. This provided strong evidence that the constraint of spatial symmetry can surpass that of motor symmetry in certain conditions. The aim of this current study was to extend these findings to test whether these same principles also held true for between-person coordination. In this chapter the tendency for 'sudden phase shifts' was exploited to *independently* investigate the variables of spatial and motor symmetry in dyad coordination.

In everyday life, individuals rely heavily on social interactions to carry out both personal and shared goals. This social interaction takes the form of perceptual and physical exchanges. Evidence has begun to emerge showing that the way individuals perceive and interact with others appears to be determined not only by the constraints and idiosyncrasies of the self, but also by factors related to one's action partner. Even when there is no explicit shared goal, the mere presence of another individual may have implications for how one subsequently perceives, codes and acts upon the environment (Sebanz, Knoblich, & Prinz, 2003). For instance, it has been shown that people are faster to produce a finger response when they observe a task-irrelevant but similar finger movement than compared to when they observe an incompatible finger movement (Brass, Bekkering, & Prinz, 2001).

Just how and why the presence of another individual should affect one's own performance is still very much under debate. Some believe this is due to the existence of shared representations between events which are perceived and events which are being planned. This has been termed common-coding theory (see Prinz, 1997) and its principles have been used to explain the compatibility and interference effects observed in studies such as Brass et al. (2001). When watching another person execute an action congruent to the one expected to be subsequently performed by the observer, the observed action helps 'prime' later performance. In contrast, when observing an incongruent action, the activated representation is at odds with the representation which must be activated in order to perform the task. The competition between these representations is theorized to result in an interference effect, which has been demonstrated by slower reaction times in producing an action response after observation of an incongruent movement (e.g., Brass et al., 2001) and also as increased variability in ongoing performance (see Kilner, Paulignan, & Blakemore, 2003).

Still others propose that certain behaviours, notably between-person coordination, may be driven more by perceptual information than by the congruence of motor representations. In an important work, Mechsner et al. (2001) revealed that during bimanual coordination, motor congruency can be overridden by spatial congruency in certain circumstances, so that movements in the same direction of motion were more stable than movements of the same type (i.e., movements activating the same muscles and hence also equivalent motor representations). In short, this finding is dramatic because it raises issues surrounding the relative importance of perceptual versus motoric information in contributing to aspects of human behaviour. A key purpose of the current study was to extend (and potentially validate) the results of Mechsner et al. (2001) in a between-person paradigm, that is, to specifically assess the independent contributions of spatial and motoric information in helping maintain interpersonal coordination.

2.1.1 Unconscious Coordination

Increasingly there has been a great deal of work looking into intentional and unintentional or 'unconscious' coordination that often arises between co-acting individuals. Yawning is perhaps one of the clearest examples of the contagious automatic nature of certain observed actions (Provine, 1989). This unconscious form of mimicry has been termed the 'chameleon effect' and has usually been studied covertly (Chartrand & Bargh, 1999). In Chartrand and Bargh (1999), participants interacted with a confederate that rubbed their face and later another confederate that shook their foot. During these separate exchanges, participants were found to selectively—and, more importantly, *unknowingly*—mimic the behaviours they had observed the confederates perform.

Generally, the socio-cognitive approach explains such phenomena using the concept of action simulation (Chartrand & Bargh, 1999; Chartrand, Cheng, & Jefferis, 2002). Here, perceiving another's actions induces in the observer a mental representation of the action, which is presumed to be similar if not equivalent to the representation involved in the actual performing of that same action. More recently the literature on 'mirror neurons' has provided a neural substrate for such beliefs. Mirror neurons obtain their name from their remarkable firing properties, as they have been found to be active both during the execution as well as the mere observation of goal-directed actions (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). First discovered by researchers investigating area F5 in the ventral premotor cortex of macaques (Rizzolatti et al., 1996), more recent studies have indicated analogous areas may be present within the human brain (Iacoboni et al., 1999). Caution is warranted in extrapolating macaque discoveries to humans, however, as unlike in humans mirror neurons in macaques seem exclusively interested in object-orientated action (for instance, the grasping of a food item) and there is virtually no evidence that macaques show any of the overt imitation thought to be key to observational learning in humans (Wilson & Knoblich, 2005).

Despite the efforts of its proponents, the socio-cognitive approach has been criticized for focusing on mimicry whilst ignoring other types of interpersonal coordination, notably synchrony (Richardson, Marsh, & Schmidt, 2005). Critically, some researchers argue that mimicry can be explained by way of priming (Aarts & Dijksterhuis, 2002; Richardson et al., 2005). This elucidates the key distinction between mimicry and synchrony. Whereas mimicry does not dictate that imitated movements be correlated in a temporal way (only that the schema still be recent enough to influence behaviour), synchronous movements explicitly require just that (Richardson et al., 2005). This is an important distinction because without temporal correlation, many coordinated movements become impossible to carry out correctly—for example, performing a piano piece in time with another musician's part. Thus ecological psychologists have argued that cognitive explanations for interpersonal behaviour have failed to adequately explain just how people can unintentionally coordinate their movements in a *rhythmical* fashion so that movements between individuals can reoccur in a temporally correlated manner (Richardson et al., 2005).

2.1.2 Rhythmic Coordination

Turvey (1990) explains that ecological psychology focuses on the creation and transfer of information through perception. In contrast to the socio-cognitive perspective, dynamical systems theorists are especially concerned with the study of rhythmic movements in understanding coordination.

Using an experimental setup in which participants are required to oscillate their two outstretched index fingers at the same frequency as an audible metronome, researchers have been able to show that key criteria of modality, inaccessibility, sudden jumps, hysteresis, critical slowing down and critical fluctuations (as described in Turvey, 1990) observed in nonequilibrium systems, also appear to be present for within-person coordination (Kelso, Scholz, & Schöner, 1986; Scholz, Kelso, & Schöner, 1987; Schöner & Kelso, 1988). In line with these criteria, it has been observed that whilst people can reliably maintain both in-phase (0°: both limbs at same place in cycle at same time) or anti-phase (180°: limbs at opposite place in cycle at same time) patterns between two oscillating limbs, they struggle in maintaining phase relations outside of those two values (Kelso et al., 1986; Kelso, Schöner, Scholz, & Haken, 1987). Furthermore, the 'sudden jump' criterion requires that a slow change of the control parameter (here, frequency) should result in a rapid change in the order parameter (here, phase angle). This has indeed been shown to occur, as a slow increase in the frequency of oscillation results in anti-phase movements spontaneously transitioning to in-phase movements (Kelso et al., 1986; Scholz et al., 1987; Schöner & Kelso, 1988). In support of 'hysteresis', which requires that the sudden jumps occur at different values of the control parameter depending on recent history (i.e., at different frequency values when ascending or descending), it has been found that in-phase movements do not transition to anti-phase movements at higher frequencies. What's more, reducing the frequency will not reverse a previous shift from anti-phase to in-phase.

Finally, 'critical slowing down' and 'critical fluctuations' have also been observed such that as the frequency increases, there are a greater number of increasingly large deviations from the anti-phase pattern observed and these deviations take increasingly longer to correct themselves back to anti-phase (Kelso et al., 1986; Scholz & Kelso, 1989; Schöner, Haken, & Kelso, 1986). The level of fluctuation in the relative phase is seen as indicative of the stability of coordination and it seems that at some critical frequency, anti-phase patterns become unstable whilst in-phase patterns remain stable (Zaal, Bingham, & Schmidt, 2000).

2.1.3 Between-Person Coordination

Of particular relevance to the current research, the properties described in the previous section have also been found to hold true for between-person coordination. The step from within-person to between-person coordination, however, should not be regarded as a trivial matter. Undeniably the great challenge in explaining between-person coordination has always been that that co-acting individuals do not share a common neural nor indeed cognitive mechanism to allow such coordination to take place in the first place (Schmidt, Carello, & Turvey, 1990). In one study, two participants sat beside one another and were asked to swing one of their legs at the same frequency as an auditory metronome whilst also coordinating their movements with their partner in either a symmetric in-phase mode or asymmetric anti-phase phase mode (Schmidt et al., 1990). When the frequency of oscillation increased, it was found that, akin to single-person coordination, between-person coordination during anti-phase trials became increasingly unstable and eventually spontaneously transitioned into the in-phase modes, but the reverse did not occur. In contrast, the symmetric phase mode showed little of the destabilizing effects of increased frequency oscillation and instead remained comparatively stable even at high frequencies. Similarly, participant pairs who were asked to coordinate the swinging of two pendulums between one another (where one pendulum was held per participant and where the pendulums' characteristic frequencies were manipulated by adjusting string length) also displayed a clear preference for in-phase and anti-phase coordination patterns, compared to phase angles between these stable states (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt & Turvey, 1994). Furthermore the anti-phase mode was found to be less stable at higher oscillation frequencies compared to the in-phase conditions.

To summarize, for between-person coordination as well as within-person coordination, at higher frequencies there appears to be a reliable sudden jump from the anti-phase mode to the in-phase mode, whereas no such jump occurs in the opposite direction. Importantly, these phase transitions do not occur when participants begin in an anti-phase mode but are not able to view the other's movement. In this sense, viewing another person's actions may impose lawful constraints on one's own potential or 'degrees of freedom' for action (Marsh, Richardson, Baron, & Schmidt, 2006). Therefore, despite differences in the neural and perceptual mechanisms involved in between-person coordination versus within-person coordination, the evidence seems to point to a common description of the behavioural dynamics. As Turvey (1990) states: “In abstract but quantifiable dynamical terms, anatomical and optical connectives between rhythmic movements appear to be identical”.

Supporting this, Goodman, Isenhower, Marsh, Schmidt and Richardson (2005) employed a more 'real life' paradigm involving rocking chairs. Here participants sat beside each other in rocking chairs and were asked to rock at their own chosen pace; weights were attached to the chairs to vary the level of frequency detuning. Participants were also asked to fixate on a target whose position determined the level of visual information available about the other participant's movements. The target could be located either on the other side of the room compared to the interaction partner (no vision condition), in front of the participant (peripheral vision condition) or on the other participant's rocking chair (full vision condition). Importantly, there was no explicit goal to coordinate rocking motions. As predicted, the level of unintentional coordination increased as the amount of visual information increased. These movements were found to be biased towards phase angles approaching 0°. Undoubtedly, such studies have shown the power visual information can have in coordination and provided clear evidence for perceptual and not just physical coupling between oscillators as here the oscillators (e.g., limbs) were not physically attached to one another and instead belonged to two separate agents.

Returning to cases of within-person coordination, there has been speculation as to why symmetric modes of oscillation should be dominant. In bimanual finger oscillation tasks, participants oscillated their index fingers in either a symmetric or parallel (anti-phase) way. It has been shown that as the frequency of oscillation increases, the parallel mode tends to spontaneously switch to the more stable symmetric mode, but the opposite does not occur (Kelso, 1984). This has been explained by a tendency for the joint activation of homologous muscles. Mechsner et al. (2001) had participants perform the same bimanual finger oscillation task and incongruent conditions (where one palm faced up and the other faced down) provided the key manipulation as a parallel rather than symmetric oscillation pattern now activated the homologous muscle groups. If the stability was due to co-activation of homologous muscles, then the parallel mode of oscillation in the incongruent position should have been preferred, as this mode now activated homologous muscles. Contradicting this reasoning, Mechsner et al. (2001) revealed that the symmetric oscillation mode was more stable than the parallel oscillation mode, which provides evidence that the need for spatial symmetry is more important than motor symmetry in maintaining phase relations. It seems, therefore, that bimanual coordination may be less dependent on motor processes and more contingent on visual processing than once thought. In summary, these findings elucidate the importance of perceptual imagery on bimanual coordination and cast doubt on a purely motoric explanation for the bimanual coordination processes.

Based on the initial findings provided by Mechsner et al. (2001) indicating that perceptual information may override motor information during synchronization in a within-person setting, a simple wrist oscillation task was designed in this chapter to investigate the role of spatial versus motor symmetry in a between-person coordination task. The tendency for phase discontinuities—that is, 'sudden jumps' in rhythmic behaviour—was exploited to study how the relative stability of in-phase and anti-phase states are influenced by spatial and motoric variables. As yet, no other researchers have applied a paradigm of this nature to look at between-person coordination. In this task, participants were sat either next to or opposite a blindfolded experimenter, whilst both oscillated one wrist to produce a combined movement which was either in-phase or anti-phase in terms of analogous muscles activation and/or spatial direction. Spatially congruent movements were defined as those in which limbs oscillated in the same absolute spatial direction of motion whilst spatially incongruent movements were those in which limbs oscillated in opposite absolute spatial direction of motion. Similarly, motor congruent movements were defined as movements which activated homologous muscle groups whilst motor incongruent movements were those which activated opposing muscle groups.

Two different dyad interaction perspectives (allocentric: face-to-face; pseudo-egocentric: side-by-side) were included in the design, which was anticipated might provide novel insight into whether one perspective might generate greater 'motor-based' (anatomical) representations than the other, as this has been a source of debate in the literature (e.g., Belopolsky, Olivers, & Theeuwes, 2008). Belopolsky et al. (2008) raised an important question relevant to perspective, which was whether an action representation undergoes a transformation before being mapped onto the observer's own body. They stated that if a perceived action were to be 'directly mapped' onto the observer's own motor repertoire, then the representation that is activated should be congruent anatomically as opposed to spatially.

2.1.4 Anatomical and Specular Imitation

Studies of imitation in young children have shown an apparent bias for mirror-like or specular imitation compared to anatomical imitation (Bekkering, Wohlschläger, & Gattis, 2000). In specular imitation, a person copies a perceived movement in a spatially congruent way. Thus if an actor facing the observer moves their right arm to their right ear, the observer should imitate the action by moving their left arm to their left ear. By contrast, in anatomical imitation the observer would also move their right arm to their right ear. Bekkering et al. (2000) investigated the degree to which children would imitate exact actions as well as end goals. It is known, for instance, that whilst monkeys often appear capable of reproducing the end goal of an goal-orientated action, they do not always do this using the same behavioural means used by the demonstrator, suggesting monkeys 'emulate' rather than imitate (Tomasello, Savage-Rumbaugh, & Kruger, 1993). Bekkering et al. (2000) noted that among children, the most common form of error occurred when the model reached out with their hand to touch the ear contralateral to the hand in question. In these unimanual trials, the children would often imitate the touch of the correct ear, but through an incorrect ipsilateral movement. By contrast, when observing an ipsilateral movement towards an ear, children rarely made incorrect contralateral movements.

Bekkering et al. (2000) explained their pattern of results by suggesting that task goals were hierarchically organized so that some goals ended up dominating others. In their unimanual task, correct ear selection dominated correct hand selection. When the task became more difficult and involved movements across body midline, the correct movement path was sometimes sacrificed to achieve the dominant goal of touching the correct ear. Belopolsky et al. (2008) notes that the reason a bias towards specular imitation is often observed is likely because the goal object (ear) may activate the effectors (hand) which are situated on the same side of the body.

Unfortunately, Bekkering et al. (2000) only included one perspective (allocentric) in their study and also instructed children to imitate in only one way (specularly). Belopolsky et al. (2008) thus became interested in studying not only whether representations of another person's action were specularly or anatomically structured, but more precisely how this differed across two perspectives. In their task, half the participants watched video clips of an actor from an allocentric perspective (facing them) and the other half watched clips of the actor taken from an angle overlooking the actor's shoulders (egocentric perspective). In both perspectives, the actor pointed at one of two lights located on the left and right sides of the table using his right or left hand with either a diagonal or straight movement trajectory. Participants performed a Go/No Go task in which they responded by pressing a button with their right hand when a particular colour change was observed and refrained from responding to any other colour change. Colour changes occurred directly after they had observed a pointing movement which cued them either in a valid or invalid way to the changing light.

Faster reaction times were unearthed when the model's hand and participant's hand were anatomically congruent compared to incongruent. Furthermore, this anatomically congruent representation appeared to be independent of perspective and persevered even when the actor pointed to an invalid cue, suggesting that an action representation persists even when spatial attention has to be shifted to the target location (Belopolsky et al., 2008). The anatomical congruence effect was seen as support for ideomotor priming where an observed action facilitates the execution of an action with a common component, so here the anatomically congruent hand is 'primed' for action. Belopolsky et al.'s finding that the allocentric perspective gave rise to anatomical representations of action is still something of a surprise given the work on imitation which has shown biases towards a specular form of action representation (Bekkering et al., 2000). As mentioned previously, this specular bias in imitation has been interpreted as the result of goal hierarchy. However, when the goals are removed such as during the mere observation of an action in the Belopolsky et al. (2008) study, anatomical rather than specular representations of action are unveiled. Belopolsky et al. (2008) speculated that had the task been to imitate, the anatomical congruence effect would likely have been reversed so that a specular representation would be preferentially adopted.

Franz, Ford and Werner (2007) also looked at differences between specular and anatomical imitation in the allocentric orientation using a task in which participants imitated a model's one-handed movement to one of two targets. They originally found an advantage for specular imitation, but found that this bias could be reversed to anatomical imitation when distinctive stimulus information (markers) were added to anatomically congruent hands in model and participant. Interestingly, they also reported evidence that whilst target selection was the dominant goal over hand selection for specular imitation, when imitating anatomically (never tested in Bekkering et al., 2000), hand selection appeared to take priority over target selection.

Franz et al. (2007) also specifically tested the idea that spatial translations (mental rotation of one's own body representation) were needed in anatomical imitation. They actively encouraged participants to imitate anatomically by suggesting to them that imagining themselves rotated through 180° (putting themselves into the model's orientation) would aid the task. In fact, what the authors observed was a detrimental slowing in responses times when such mental rotations of perspective were used, leading the researchers to question whether spatial translation (although a possible strategy) is the 'natural' mechanism employed in the anatomical imitation mode. The fact that anatomically congruent representations appeared in both allocentric and egocentric perspectives (Belopolsky et al., 2008) further suggests that some form of rapid automatic activation is likely to be operating, as opposed to a time consuming mental transformation that one might have previously expected was necessary for anatomical representations in the allocentric perspective.

Franz et al. (2007) concluded by suggesting that a direct matching between perception and action may not apply in the same way across specular and anatomical imitation. Moreover, their findings demonstrate the seemingly flexible nature of action representation during imitation and the influence that task design can play in the strategy which is naturally adopted. Further to this, Belopolsky et al. (2008) proposed that it was still logical to believe that actions in the egocentric perspective should lead to a stronger activation of the motor system, because for the most part these actions should be less ambiguous and more recognizable than actions observed from an allocentric perspective. Some evidence does appear to support this claim. For instance, Maeda, Kleiner-Fisman and Pascual-Leone (2002) showed that an observer's orientation played a role in motor facilitation while observing hand actions in either an allocentric or egocentric perspective. They recorded motor evoked potentials (MEPs) in the observer and found that observation of a movement facilitated motor output to the same muscles involved in the movement. Crucially, however, motor activation was optimized in conditions where the observed action corresponded to the orientation of the observer (egocentric) as opposed to an allocentric orientation.

As most work so far has dealt with specular imitation and allocentric perspectives, it felt important to incorporate both egocentric and allocentric perspectives into the current design. The need for this was further highlighted by the disparities in findings across different types of task. As the current task involved 'live' coordination between people instead of coordination to a video stimulus, it was not possible to include a true egocentric perspective. Instead a pseudo-egocentric perspective was employed where the model sat slightly over to the right hand side of the participant but facing in the same direction.

The final point to address regarding the current design is the exact nature of the task itself. Clearly the task was not merely observational, as participants actively executed movements. However, it is also not accurate to describe the task as purely imitative because, in at least some conditions, participants were performing in neither a spatially nor an anatomically congruent way, regardless of perspective. As the task differed from both of these scenarios, it was anticipated that it might provide novel insight into the differences in action representations already reported in observation versus imitation.

To summarize, a better understanding of the relative strength of the motor representation in between-person coordination is crucial given differences in the literature. If spatial symmetry is more dominant or 'stable' than motor symmetry, then at higher oscillation frequencies participants should be expected to more often spontaneously transition from motor in-phase modes to spatially in-phase modes. If, however, the opposite is true and motor symmetry is more dominant, then at higher frequencies spatially in-phase modes should be expected to more often switch to motor in-phase modes. The first hypothesis was straightforward in that spatially congruent conditions were predicted to be more stable than spatially incongruent conditions. Earlier transition times for spatially incongruent conditions were hence expected compared to spatially congruent conditions. Equally, it was also hypothesized that motor-congruent trials should be more stable than motor-incongruent trials. Again this was expected to manifest as earlier transition times for motor-incongruent conditions compared to motor-congruent conditions. The predictions were less certain when it came to the influence of dyad position on interpersonal coordination and thus the hypothesis was a more tentative one. It was anticipated that there might be a difference in transition times for face-to-face versus side-by-side trials, although there was no prediction with regards to the direction of this effect. Further to this, it might also have been predicted that a motor-based representation could be stronger in one dyad position compared to the other, as has been suggested in some literature (Belopolsky et al., 2008). For instance, differences between transition times for motor-congruent versus motor-incongruent trials might be more pronounced in one perspective compared to the other. The same could also be true of a space-based representation across dyad positions. Thus the main hypotheses predicted the emergence of differences manifesting as later transition times for congruent versus incongruent conditions for both factors spatial and motor factors. Furthermore, a difference in transition times across the two dyad positions was also anticipated, seen as a significant interaction between dyad position and congruence which, if found, should help shed light on the influence of orientation in determining the strength of motor representations of observed action.

2.2 Method

2.2.1 Participants

Twelve (8 female) right-handed (self-reported) students with a mean age of 24.4 years from the University of Birmingham were recruited; each received a choice of either research course credits or £4 cash for their participation. Prior to participation, each volunteer provided informed consent.

2.2.2 Apparatus and Materials

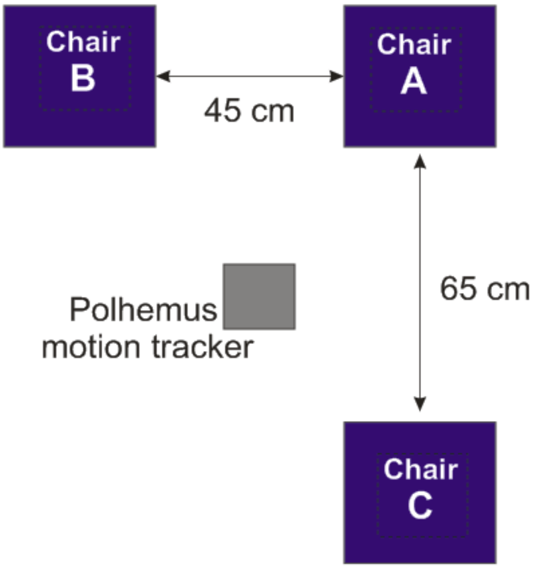
A magnetic 3D motion tracking device (Fastrak Polhemus, Colchester, VT) with a 1 mm spatial resolution was used to record the motion of two sensors each sampling at a frequency of 60 Hz. One sensor was attached to the right hand index finger of the participant using sticky tape whilst the other was secured onto a wooden thimble which the demonstrator could switch between either the index finger of the right or left hand depending on trial condition. A purpose built Matlab (Mathworks, MA) program saved the motion-capture data.

In addition, the program also ran a metronomic beep which increased in speed over time during each trial recording (2 Hz for 5 s followed by increments in speed until 5 Hz was attained). This beeping was played to the demonstrator via headphones and was not audible to the participant. Each recording lasted approximately 33 seconds.

Three identical armed chairs were positioned as seen in Figure 2.1. Chairs A and B were positioned side-by-side separated by approximately 45 cm from armrest to armrest. Another chair, C, was placed in front of and facing Chair A, separated by 65 cm. In all trials the participant remained seated in Chair A, whereas the demonstrator sat in Chair B for side-by-side (SBS) trials and Chair C for face-to-face (FTF) trials. Motion tracking equipment was placed on a wooden support stand 50 cm from the ground midway between the Chairs A and C, but positioned over on the right hand side approximately midway between Chairs A and B. This ensured the Polhemus did not obstruct the view of the participant during FTF trials.

Figure 2.1 Experimental set-up.

Participants always sat in Chair A. The demonstrator changed seating positions between Chairs B and C, depending on the trial condition.



2.2.3 Design and Procedure

The experiment conformed to a 2 (dyad position: face-to-face (FTF), side-by-side (SBS)) × 2 (motor congruence: congruent, incongruent) × 2 (spatial congruence: congruent, incongruent) within-participants design. Motor-congruent (in-phase) movements were defined as movements which activated analogous muscles (wrist flexors or extensors) simultaneously in both demonstrator and participant, whilst motor-incongruent (anti-phase) movements were movements that activated opposite muscles in the participant compared to the demonstrator (experimenter). In the same vein, spatial congruence referred to movements where the absolute spatial direction of motion of the movements performed by the demonstrator and the participant were either the same (congruent or in-phase) or opposite (incongruent or anti-phase) in absolute spatial direction of motion.

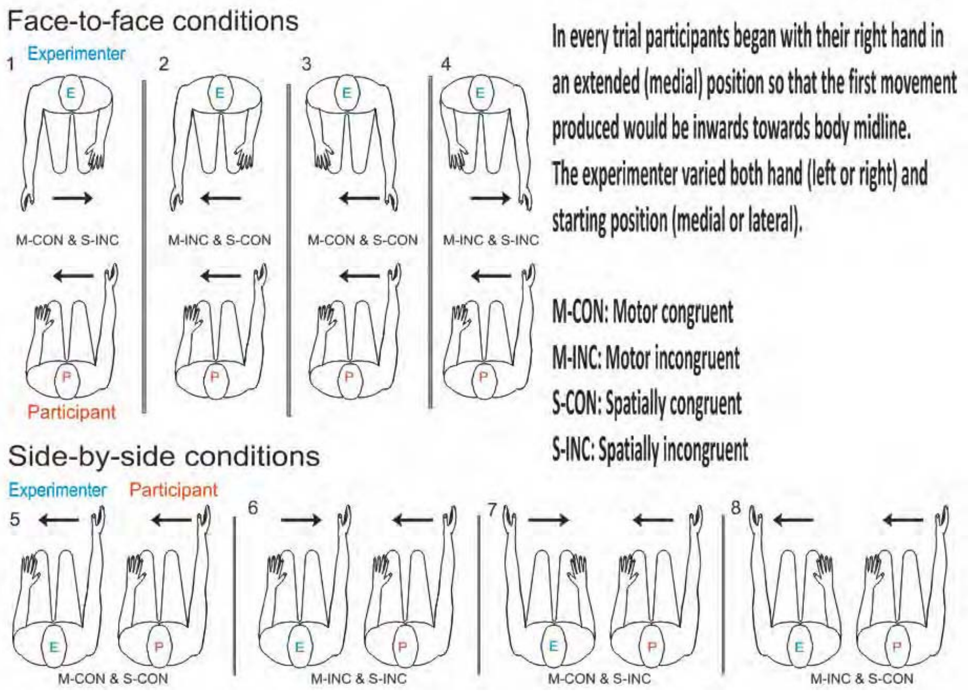
Trials were performed with participant and demonstrator seated either next to one another (SBS) or faced opposite one another (FTF), depending on condition. Participants always performed the same movement using their right hand beginning in a medial (extension) starting position so that the first movement would bring the face of the hand in towards the body. The experimenter, however, changed between the left and right hand on different trials whilst also varying the starting position so as to begin with their hand in either a medial (extension) or lateral (flexion) starting position depending on condition. There were eight experimental conditions performed in blocks (outlined in Table 2.1 and displayed pictorially in Figure 2.2). The conditions within each block were randomized and in total there were four blocks so that overall participants performed thirty-two trials in a pseudorandom order (four trials per condition).

Table 2.1. Experimenter starting positions. Numbers on the table correspond to labelling in Figure 2.2.

	Spatially congruent (S-CON)	**Spatially incongruent (S-INC)**
FACE-TO-FACE		
Motor congruent **(M-CON)**	Demonstrator begins with **left hand** moving **inwards** (3) (M-CON & S-CON)	Demonstrator begins with **right hand** moving **inwards** (1) (M-CON & S-INC)
Motor incongruent **(M-INC)**	Demonstrator begins with **right hand** moving **outwards** (2) (M-INC & S-CON)	Demonstrator begins with **left hand** moving **outwards** (4) (M-INC & S-INC)
SIDE-BY-SIDE		
Motor congruent **(M-CON)**	Demonstrator beings with **right hand** moving **inwards** (5) (M-CON & S-CON)	Demonstrator begins with **left hand** moving **inwards** (7) (M-CON & S-INC)
Motor incongruent **(M-INC)**	Demonstrator begins with **left hand** moving **outwards** (8) (M-INC & S-CON)	Demonstrator begins with **right hand** moving **outwards** (6) (M-INC & S-INC)

Note: Participants always began with their right hand moving inwards.

Figure 2.2 Experimental trial conditions. Numbers correspond to information in Table 2.1.



In every trial participants began with their right hand in an extended (medial) position so that the first movement produced would be inwards towards body midline. The experimenter varied both hand (left or right) and starting position (medial or lateral).

M-CON: Motor congruent
M-INC: Motor incongruent
S-CON: Spatially congruent
S-INC: Spatially incongruent

Each participant was tested individually. After reading through instructions, participants were seated in Chair A with their arm supported by an armrest. Participants learned that they would be making wrist movements whilst watching the experimenter also perform wrist movements that could be either similar to or dissimilar to the action the participant was him/herself performing. Participants were informed that they were to keep 'equal pace' with the experimenter so as to match their oscillation frequency. Participants thus watched the movements being executed by the experimenter whilst simultaneously producing their own movements. Throughout each trial, the experimenter maintained their eyes closed so that their own movements would not be contaminated by the visual information from the participant's movements. A sensor was secured onto the participant's right hand index finger; on each trial, the participant always produced wrist movements which began with an 'inward' movement, towards the body. The experimenter demonstrated the movement prior to beginning the experiment. The experimenter switched chairs and type of movement according to experimental condition.

On each trial, the experimenter listened to a metronome whose speeding up increased over time. As a consequence, the experimenter was required to speed up their movements in order to keep in time with the metronome. Thus, when the experimenter increased the speed of their movements, the participant aimed to do the same. Non-intervention instructions were employed. This meant that in the event that the participant found it too difficult to keep to the initial phase relationship (i.e., the relative hand configurations at the start of the trial) and as a consequence fell out of this initial configuration (i.e., transitioned) due to the increasing frequency of oscillation for instance, then they should simply carry on and not attempt to stop or correct their movements.

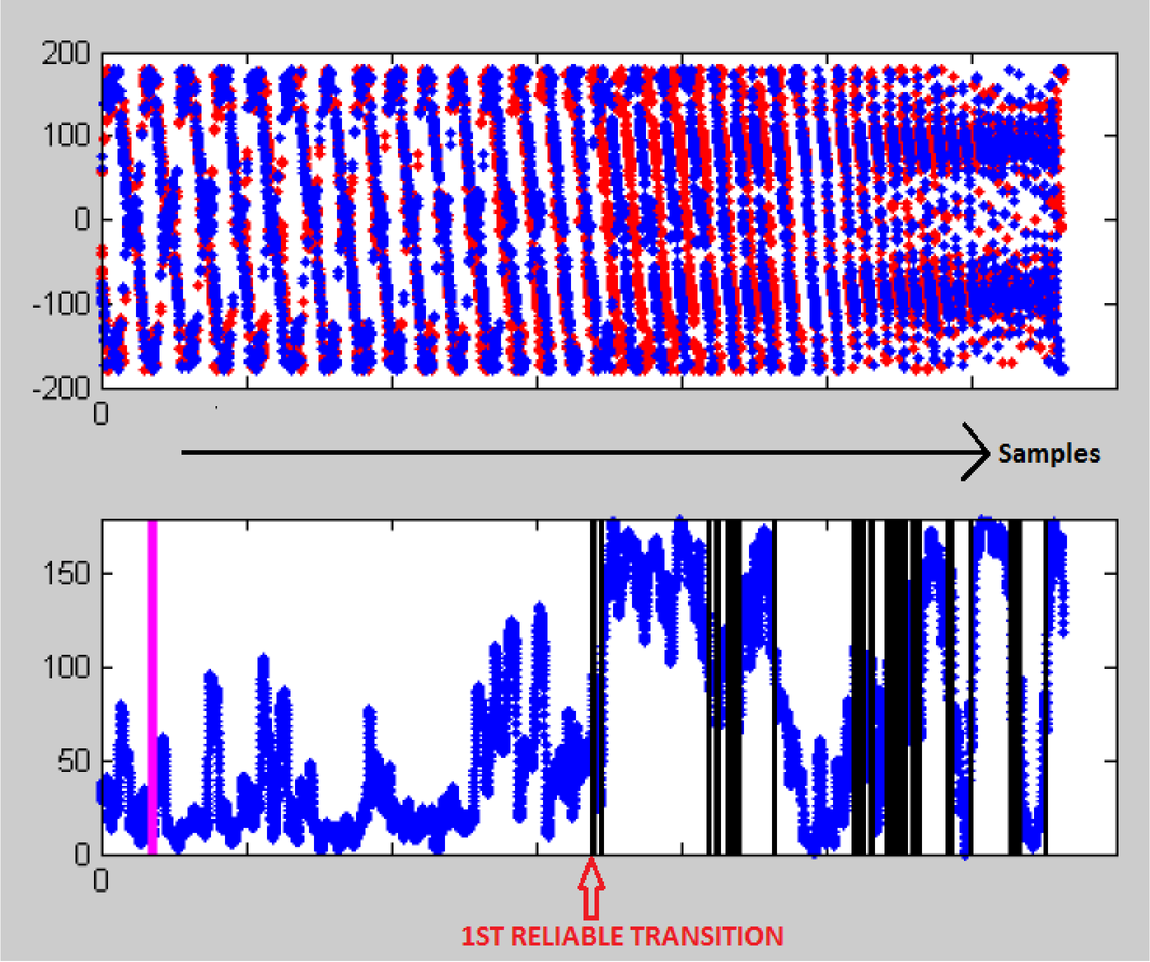
2.3 Analyses

All movements were analysed with reference to their spatial congruence. Spatially in-phase movements were those movements with a phase angle at or approaching 0°, whilst spatially anti-phase movements were at or close to a phase angle of 180°. A transition from in-phase to anti-phase or from anti-phase to in-phase was said to occur when the phase angle crossed the halfway point (90°) from either direction. An in-house Matlab script was used to detect the time of the first transition in participants' movement data, where the phase angle passed through 90°. Only phase transitions that switched from one phase into the other phase for a reliable period of time (approximately 500 ms or longer) were considered true transitions (Figure 2.3). Generally, these true transitions resulted in a genuine change from one phase condition all the way to the other phase condition, thus passing well beyond the 90° mark. Momentary transitions lasting only a few hundred milliseconds which never went dependably beyond 90° to attain the 'new' phase were ignored as these were not considered to be reliable examples of true phase shifts (i.e., 'sudden jumps') and probably reflected instead micro-corrections made by the participant in order to keep pace with the experimenter's change in speed as the trial progressed. In such cases, the time of the next reliable phase transition would be selected for analysis. The only time momentary transitions were accepted as true transitions were in rare cases when participants' began either in a reliably characterized in-phase (0°) or anti-phase (180°) position and later transitioned to 90° (but not reliably beyond/below this point) several times in quick succession. Thus it appeared that the phase angle was 'hovering' for some time at the 90° neutral point where movements were neither in-phase nor anti-phase, before finally transitioning to the new phase or returning to the original phase. If there were no reliable transitions contained within a trial, the time chosen for analysis was that of the last point sampled (i.e., the endpoint of the trial), which varied very slightly due to recording equipment but was roughly the time at 1980 samples.

The initial five seconds of data from each recording was discarded. The earlier the transition, the less stable the trial condition was hypothesized to be, as early transitions suggest that the participant was quicker to spontaneously transition from an unstable phase angle into the presumably more stable phase angle. Later transitions or no transitions would indicate that the trial was more stable, as the participant was able to keep pace with the experimenter despite the increase in speed. Therefore, if the participant was already in a stable phase, it would be unlikely that they would transition out of this phase into a less stable phase angle, as phase transitions are thought to occur in the direction that would maximize stability and not the other way around. At excessively higher speeds, however, transitions might occur even in stable conditions because the increased speed undermines the stability of the whole system. For each participant, the time of the first true phase transition was averaged across the four repetitions of the same trial. This resulted in each participant producing eight averages, one for each of the eight trial types. Statistical analyses were performed on these averages obtained from the 12 participants. Where characterization of the dominant phase was ambiguous, usually because of frequent oscillation around the median point of 90°, these trials were excluded from analyses. Trials were also excluded if the participant began incorrectly and did not correct for this within 10 seconds (600 samples). These excluded or 'bad' trials were infrequent and accounted for approximately 4.7% (18/384 trials) of the overall data.

Figure 2.3. Example of a phase transition.

Upper panel shows experimenter (red) and participant (blue) motion traces in space. Lower panel shows relative phase angle.

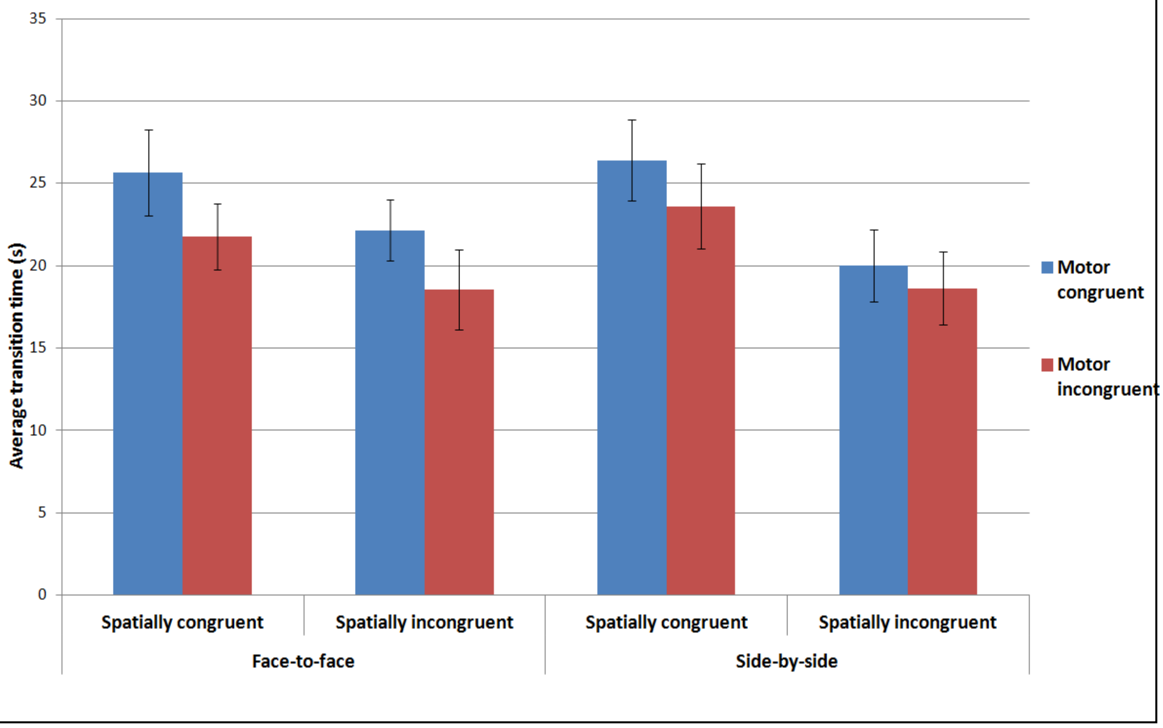


2.4 Results

A 2 (dyad position: face-to-face, side-by-side) × 2 (motor congruence: congruent, incongruent) × 2 (spatial congruence: congruent, incongruent) within-subjects ANOVA was performed using each participants' average times for the first phase transition of each of the eight trials conditions, described previously. The ANOVA revealed a significant main effect of spatial congruence, $F(1, 11) = 32.65$, $p < .001$, $\eta_p^2 = .75$, and a significant main effect of motor congruence, $F(1, 11) = 8.64$, $p < .05$, $\eta_p^2 = .44$ (Figure 2.3). The main effect of dyad position was not significant, $F(1, 11) = 0.01$, $p > .05$, $\eta_p^2 = .00$. No interactions approached significance, ($p > .05$).

In both dyad positions, spatially congruent and motor-congruent trials appeared more stable than spatially incongruent and motor-incongruent trials respectively, as indicated by the later transition times for the former conditions. The average time of the first phase transition for spatially congruent trials, ($\mu = 24.37$ s, $SE = 2.13$ s) was considerably later than the average time of the first phase transition for spatially incongruent trials, ($\mu = 19.84$ s, $SE = 1.86$ s). Similarly, the average time of the first phase transition for motor-congruent trials, ($\mu = 23.56$ s, $SE = 1.99$ s) was notably later than the average time of the first phase transition for motor-incongruent trials, ($\mu = 20.65$ s, $SE = 2.06$ s).

Figure 2.4 Average phase transition times for the different spatial and motor congruency conditions in both face-to-face and side-by-side trials. (Error bars represent ±1 standard error of the mean).



2.5 Discussion

This chapter examined the role of spatial and motoric information in interpersonal coordination stability, by independently manipulating congruency between participant and model along these two dimensions. The influence of viewing perspective in modulating such contributions was also tested.

The results confirmed that both spatial and motoric (anatomical) congruence impact on the ability to maintain stable coordination behaviour during between-person interactions. The motor congruency effect revealed that participants were better able to keep their movements coordinated as instructed when both their wrist movements and the demonstrator's wrist movements activated homologous muscles compared to when these movements activated opposing muscles. This was evident by earlier phase transition times for motor-incongruent conditions compared to motor congruent conditions, suggesting that motor-incongruent trials were considerably more difficult to maintain. This finding supported the hypothesis that motor-congruent trials would be more stable than motor-incongruent trials, as fluctuations in the relative phase are suggestive of the stability of coordination (Schmidt et al., 1990; Zaal et al., 2000). This result also lends credence to the findings of Belopolsky et al. (2008), who found a reaction-time advantage for anatomical congruence across both egocentric and allocentric perspectives. Importantly, their task objectives were dissimilar to those in this current study, as they employed a Go/No Go task. Although their task was not devoid of goal entirely, as their participants still had to respond to changes in their environment, clearly the task represented in their study was not as directly linked to the observed action in the same way that imitation of an action might be. By the same token, the goal in this current task was for participants to keep in the correct configuration, which required matching the pace set by the experimenter. This was not the same as 1:1 imitation per se, as in certain instances participants neither imitated anatomically or spatially, nor would it be true to refer to the task as merely observational.

Similarly to the motor congruence effect, the results revealed that participants performed better when they carried out movements which were in the same spatial direction of motion as the movements performed by the experimenter, compared to when the spatial direction of participant and experimenter movements mismatched. Again this manifested as earlier transition times for spatially incongruent trials compared to spatially congruent trials, suggesting that spatially incongruent movements made coordination harder to maintain as the frequency of oscillation increased. This supported the hypothesis that spatially congruent trials should be more stable than spatially incongruent trials and furthermore it reconfirmed the spatial compatibility effects reported previously by others (Brass et al., 2001; Mechsner et al., 2001).

It should be noted that spatially congruent and motor congruent trials were more stable than spatially incongruent and motor incongruent trials, respectively, irrespective of dyad position. Indeed, there was no main effect of dyad position, nor any interactions involving this factor. This went against the prediction that there might exist differences between the allocentric and egocentric perspectives. Consequently, it was not possible to conclude that either perspective is more advantageous in helping maintain stable between-person coordination. Nor was it possible to provide evidence in support of the notion that different vantage points might induce greater degrees of anatomically versus spatially based action representations or vice versa.

This null result may have been at least in part due to the pseudo-egocentric perspective adopted in the paradigm due to the live nature of the interactions tested. This may not have mimicked in an adequate enough manner a true egocentric perspective. If so, the pseudo-egocentric condition might not have been able to elicit either the same strength of action representation or perhaps even the same type of action representation found in a true egocentric orientation. A suggestion for how to more carefully control this in future would be for the movements of the model to be shot from a camera angle above their shoulders and for these actions to be directly played to the participant in real-time via a head-mounted display for example. However, such measures only raise more issues surrounding the ecological validity of such procedures and further highlights the trade-off which is the bane of studying human behaviour naturally, but empirically.

The ideal situation, of course, would be to able to study temporal and spatially coordinated behaviour in much the same way as mimicry has been studied, namely, naturally but covertly (Chartrand & Bargh, 1999). Unintentional coordination such as mimicry represents only one type of interpersonal coordination and thus so far has failed to offer insight into how individuals perform synchronized actions (Richardson et al., 2005). Clearly, if the study of between-person coordination is the objective, then the optimal means to achieve this goal is though the direct 'real-life' study of live individuals engaged in active tasks. In fact, it has been demonstrated that the mere presence of others can have consequences for one's own motor behaviour and on the successfulness of the task at hand (Sebanz et al., 2003). In this sense the methodologies employed by socio-cognitivist and ecological psychologists, from which this current work was derived, have provided the foundation on which to pursue future work.

One important question raised and an avenue for possible future research is the degree to which social engagement might influence motor behaviour. Goodman et al. (2005) noted, for instance, that the level of visual information available about another participant's movements influenced concurrent spontaneous coordination behaviour with that person. Coordination increased as focal attention was directed more fully towards the interaction partner compared to when this partner was out of view. Whilst these authors did not frame their result with any social 'undertone', it could be argued that varying the level of perceptual visual information available about the other person also varied the level of social engagement. Might, for instance, performing with another person have implications for the level of effort one puts into a task, as one might predict a greater social obligation to perform the task correctly and to attend to the task in general when another task partner is present? In the current design, the demonstrator always maintained their eyes closed and one could pose the question of how socially engaging this really was. Compared to being directly observed, this might have resulted in participants feeling as though they were not being truly monitored, which could have resulted in participants being less inclined to perform correctly or even attend to the task.

Furthermore, it could be suggested that perhaps the goal of the task was simply not salient enough to evoke differences across perspectives, as the wrist actions employed were not object-orientated in the way that they might have been if, say, participants were beating a cymbal. However, other researchers have successively shown evidence of motor interference effects (assumed to be the result of incongruencies in the motor representations of simultaneously observed and executed actions) on actions that were not goal-directed either (Kilner et al., 2003). Nevertheless, the finding here in support of motoric as well as spatial representations for observed actions in the allocentric perspective is somewhat unexpected given the evidence in favour of specular imitation (Bekkering et al., 2000). Franz et al. (2007), however, did report that although a specular advantage in imitation does appear to exist, anatomical representations can be brought about through the addition of distinctive stimulus information (i.e., placing markers on the anatomically homologous hands in model and participant). Although stimulus information was not manipulated in this way (which could be a worthy avenue for future research), it is possible that participants were consciously or unconsciously employing different strategies across the different trial types. They might for example be focusing on different pieces of information depending on orientation and spatial and/or motor congruence of a given trial. For instance differential coding of goals may have been at play, where some trials were interpreted as 'imitation' (e.g., spatially and motorically congruent trials) and others were not (e.g., spatially and motorically incongruent trials). Such drastic shifting of action representations across trials hardly seems a parsimonious account of coordination behaviour, however. As Franz et al. (2007) noted when they asked participants to perform mental rotations so as to 'aid' task performance during anatomical imitation trials, execution response times actually deteriorated. This underpins the notion that whatever process is naturally employed must be an efficient one.

In conclusion, this chapter has demonstrated that both spatial and motor compatibility affects the stability of coordination between individuals and this appears to be independent of dyad perspective at least within the specific task goals set out in the current instructions. Nevertheless, much more work in this area is still warranted to elucidate whether perspective does indeed induce differences in action representations and, in order to do this, the choice of what represents an egocentric perspective needs to be more carefully controlled. Although it seems likely that both spatial and motoric information influences motor behaviour, future work should aim to tease apart more precisely the specific conditions which favour one source of information (spatial versus motor) over the other and vice versa. The implications for this type of research are central for ideas linking perception and action, and more generally for concepts surrounding observational learning where such research might suggest which conditions are optimal for learning an action-based skill.

CHAPTER THREE[1]

BOTTOM-UP AND TOP-DOWN MODULATION OF SENSORIMOTOR SYNCHRONIZATION

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[1] This work was a collaborative project with fellow student Juliane Honisch

3.1 Introduction

This chapter will describe an experiment which assessed the influence of bottom-up and top-down information on the ability to synchronize to movements portrayed in a point-light display in which 3D motion recordings were projected on screen using a stereoscopic procedure. Stimuli were derived either from a previous recording of the participant's own movement or from a recording taken from another agent, unknown to that participant. Belief surrounding the provenance of the movement in the display was manipulated with the aim of extending the findings of previous research, which has advocated attention and gating mechanisms for top-down modulation of movement production (Liepelt & Brass, 2010).

The ability to accurately perceive, interpret and predict the actions of other agents during social interactions appears vital. These occasions critically hinge on people's ability to engage effectively with others and very often they require action response. For example, it may be necessary to coordinate behaviour towards a mutual goal, such as carrying a piano upstairs. The study of how the observation of movement impacts on the perceiver's own subsequent actions, therefore, has both enormous relevance and implications to understanding core human behaviours, as well as possibly opening up avenues for clinical application in motor rehabilitation. Examining synchronization behaviour is one approach to this area of study. A novice synchronized swimmer would, over time and with training, improve their synchronization until eventually becoming expert. However, what allows this improvement to occur and, more relevant to the goal of this current chapter, how could this progression be fast-tracked or enhanced further through the use top-down instructions? This chapter focused on using synchronization as a tool to study the influence of bottom-up and top-down processing in synchronization to biologically derived motion stimuli.

3.1.1 Synchronization and Self-recognition of Movement

To study the perception of biological motion patterns, Johansson (1973) developed the point-light method in which recordings were made of small lights attached to an actor's main joints whilst they performed an action such as walking or dancing. As only the light points were visible, non-kinematic cues were absent, leaving abstracted recordings which convincingly evoked the sense of the recorded movement using only 10 points. Despite being stripped of familiarity cues, people viewing point-light stimuli have shown above-chance recognition of both the gender and the identity of the agent in the display when this agent was a familiar friend (Cutting & Kozlowski, 1977). Interestingly, some have reported self-recognition of whole-body movements to be better than friend-recognition, even when the displays are presented from a third-person perspective (Beardsworth & Buckner, 1981). As Cook, Johnston and Heyes (2011) noted, this finding is interesting because although people are familiar with viewing others from this perspective, self-produced action is 'perceptually opaque' (Heyes & Ray, 2000) as it cannot be viewed directly from this third-person viewpoint. Whilst mirrors or video recordings afford people an infrequent view of their self-produced actions, the advantage for self-recognition over friend-recognition provides evidence that the motor system itself influences perception. Otherwise, if recognition is driven purely from visual experience, a bias in friend-discrimination would surely prevail.

Cook et al. (2011), however, go on to argue that the point-light technique is unsuited to self-recognition as, firstly, residual cues pertaining to the actor's physique are still present in the display and, secondly, the unusual markers worn during recordings might lead to constrained movements. To examine sources of information to account for this difference in friend- versus self-recognition, Cook et al. independently manipulated the temporal and spatial features of avatar stimuli constructed from footage of facial motion. Disrupting configural face processing through stimulus inversion impeded friend recognition but not self-recognition, suggesting that the ability to recognize familiar others under such conditions relies on configural (spatial) topographical cues. The self-recognition advantage disappeared, however, when temporal features of stimulus motion were altered by slowing or disrupting the rhythm of stimuli. Accordingly, the authors speculated that the self-recognition advantage might arise through learning over time to correlate the temporal characteristics of one's actions with the first-hand sensorimotor (i.e., visual, vestibular, proprioceptive, somatosensory, etc.) experience.

The self-recognition advantage has been found not only for observation of whole-body movements, but also in a study requiring participants to synchronize to auditory clips of piano pieces, which had previously been recorded from either their own performance or that of another piano player (Keller, Knoblich, & Repp, 2007). Participants in this study recorded one part of several piano duets and returned several months later to perform the other complementary piece of music for each duet. Pianists were found to be significantly better at synchronizing to their own recordings than to the recordings of another player. This supports the hypothesis that less discrepancy occurs for simulation and observation of self-generated actions because simulation takes place in the same motor system that produced the observed action (Knoblich & Flach, 2003). Thus the auditory information present in Keller et al. (2007) appeared sufficient to evoke an internal representation of how the accompanying musical part might be played. The participant could then synchronize their own performance against this internal simulation, which would match more accurately for self-generated performances by virtue of being mapped onto the same motor system, hence giving rise to the improved synchronization with one's own recordings. In addition, it was noted by Keller et al. that participants who were particularly good at synchronizing with their own recordings were also much more likely to identity those recording as their own when asked to judge the performer of various recordings as self or other. On the basis of their findings, the authors concluded that action simulation might be critical to both synchronization and self-recognition.

Some might argue that the especially expressive nature of musical performance itself might have permitted improved self-recognition. However, the self-recognition advantage has also been reported in other studies involving self versus other discriminations of size-normalized handwriting traces (Knoblich & Prinz, 2001) and clapping sequences stripped of all acoustic information except for tempo and rhythm (Flach, Knoblich, & Prinz, 2004). In one study (Flach et al., 2004), participants recorded clapping sequences, which were later translated into beep sequences that retained the original relative timing, but which were replayed using another participant's tempo. Under these conditions, participants could no longer reliably identify their own clapping, suggesting that both relative timing and tempo play a role in self-recognition. Otherwise, had only tempo information been used to aid self-other discrimination, participants should have mistaken other's recording for their own. Equally, if only relative timing was needed for self-recognition, participants' discrimination performance should have been unaffected by the use of another's tempo.

Taken altogether there is a large body of evidence to support the idea that action knowledge may mediate the self-recognition advantage, which appears to be a fairly resilient phenomenon that prevails even under conditions in which the visual cues are abstracted or presented from a third person perspective. In particular, the hypothesized shared representations between action perception and action execution have been highlighted (Keller et al., 2007).

3.1.2 Influence of Others' Movement

Kilner, Paulignan and Blakemore (2003) investigated the links between perception and action using an interference paradigm in which participants performed vertical or horizontal arm movements whilst concurrently watching an actor or robot arm performing the same or the orthogonal action. Participants showed increased variability (measured as movement in the plane orthogonal to intended movement) when they observed human actions incongruent with their own. By contrast, observing robotic arm movements failed to reproduce an interference effect, bolstering support for biological motion playing a critical role in 'motor contagion' in humans, irrespective of whether the movement is goal-directed or not (Blakemore & Frith, 2005). Notably, however, Stanley, Gowen and Miall (2007) found that interference effects were present when observers performed movements whilst watching a dot stimulus representing either biologically plausible or implausible (i.e., flat velocity profile) motion. Critically, interference was contingent on the belief that the stimulus was of biological origin. Believing the stimulus to be computer-generated yielded no interference effect, even when motion was, in fact, biologically-driven. The authors stated that agency-belief (biological or non-biological) was capable of influencing the processing of the stimulus on later integration within the motor system. They suggested that the interference observed for non-biological motion during human-belief conditions might have been due to participants imagining the unobserved arm movement and hence evoking a motor representation leading to interference during incongruent conditions. Supporting the idea of action simulation, macaque mirror neurons have been found to fire in a temporally-correlated manner during the grasping of a food item even when the critical interaction between the agent and the to-be-grasped object is obscured from view (Umiltà et al., 2001).

The research conducted by Stanley et al. (2007) raises two interesting points: firstly, that the interference effect is subject to top-down influence and, secondly, that non-biological motion can affect measures, which were previously believed to be responsive only to biological agents. Furthermore, Liepelt and Brass (2010) showed that belief about animacy modulated performance in a motor priming task. These tasks typically require participants to execute one of two finger actions dependent upon which number cue presents itself on a screen in close proximity to a task-irrelevant hand, also onscreen; the task-irrelevant hand performs either a congruent or incongruent action to the one cued by the number (Brass, Bekkering, Wohlschläger, & Prinz, 2000). Liepelt and Brass used a variant of the task in which the onscreen hand was gloved and belief surrounding its animacy was manipulated prior to the task by exposing participants either to a real gloved human model or a gloved wooden-hand analogue. Participants from both belief groups showed a motor priming effect (i.e., shorter reaction times during congruent rather than incongruent observed action). However, the effect was more pronounced for participants who believed the onscreen hand was a gloved human hand, despite both groups having viewed identical stimuli.

Liepelt and Brass (2010) suggested two possibilities for how agency-belief modulated motor priming. The first of these, an attentional hypothesis, was championed originally by Longo and Bertenthal (2009) to explain the reduced motor priming that occurred when their participants were explicitly informed that they were observing a computer-generated hand as a stimulus. The authors suggested that whilst the artificiality of their stimulus remained in subsidiary awareness, the stimulus was processed as though it were a real hand. However, by explicitly drawing into focal attention the artificiality of stimulus, it could no longer be processed like a real hand would be and the bias to imitate was thus attenuated. The second interpretation offered by Liepelt and Brass was a 'gating hypothesis', whereby only movements which are believed to be biologically-driven (i.e., intentional) are granted access to the mirror system and are hence prone to interference. Once access is granted, observed movements, whether biological or not, are internally simulated within the mirror system and mapped through the process of direct-matching onto the motor program required to perform that same action. Any discrepancies between the motor representations activated for concurrently observed and executed movements are then hypothesized to give rise to interference (motor contagion) in the ongoing outputted movement (Blakemore & Frith, 2005). Therefore, the believability of the stimulus as being biological appears to be vital as to whether an action is given privileged access to the mirror system, and this gating procedure may be functioning at an implicit rather than conscious level (Liepelt & Brass, 2010).

Using functional magnetic resonance imaging, Stanley, Gowen and Miall (2010) also revealed different patterns of brain activation contingent on whether participants believed that they were observing human- or computer-generated point-light movement. Specifically, greater activation within the ventral paracingulate cortex was noted for stimuli believed by participants to be human, irrespective of their true agency. Similarly, the dorsal paracingulate cortex showed increased activity when the explicit agency-belief instruction (human or computer) conflicted with the biological realism of the stimuli, which were composed of original human recordings scrambled to create a range of low to high realisms. Indeed, the ventral paracingulate cortex has been implicated in evaluating similar (biological) others, whereas the dorsal region appears to process judgements of dissimilar others (Jenkins, Macrae, & Mitchell, 2008; Mitchell, Banaji, & Macrae, 2005; Mitchell, Macrae, & Banaji, 2006). Stanley et al. indicated that the former result is consistent with the increased ventral paracingulate activity for stimuli construed as human in their study. Equally, they suggested that the latter reported increased activity in the dorsal paracingulate is comparable to that observed in their study during the processing of ambiguous stimuli under conditions where belief instructions and stimulus realisms were particularly incongruous.

In the behavioural component of their experiment, Stanley et al. (2010) tasked their participants with rating the degree of match between the instructed agency-belief category and their subjective perception of the display. The results revealed that participants were more likely to rate a low-realism trial as human when the stimulus was explicitly introduced as being of human origin. Thus the results add to the evidence suggesting that agency-belief can influence, both at a neuronal and a behavioural level, the perception and consequent processing of motion stimuli.

Overall, Stanley et al. (2010) concluded that the paracingulate cortex might be the key to allowing intentionality to be attributed to a movement which, if granted, would give rise to interference effects. Presumably, this brain region could serve as the 'gate keeper' in the gating hypothesis put forward by Liepelt and Brass (2010), although this would require targeted investigation. Indeed, Stanley et al. advocated the paracingulate cortex as a key processing region of the brain involved in overseeing the interaction of bottom-up stimulus-driven information with top-down instructions. Interestingly, mirror neuron areas were not activated during human-belief conditions in their task and instead activation was found in regions pertaining to more general social understanding such as the medial prefrontal cortex, believed to influence perception of human agency (Wheatley, Milleville, & Martin, 2007). Stanley et al. indicated that the absence of mirror neuron activity might have reflected the abstractness of their stimuli in combination with the passive observational nature of their task, concluding that further research is warranted involving tasks which require active simulation. To this end, the present study pursued a behavioural investigation of how top-down belief instructions influence performance in a task requiring active synchronization.

3.1.3 The Current Study

Point-light methodology was employed to create whole-body stimuli recordings of distinct intransitive (i.e., not object-directed) arm movements. Intransitive movements were chosen as these did not have prior behavioural connotations. Participants were asked to synchronize their arm movements to those present in the stimuli recordings that were derived from either their own movement or that of another agent unknown to them. Participants first performed the task whilst explicitly unaware of the identity of the actor they were watching and later they were given information on each trial regarding the agent's identity. Crucially this information was either truthful or misleading in nature, thus creating four belief conditions. Participants either knew the correct identity of the actor (self, other) or they were led to believe the actor in the display was or was not themselves, when in fact the opposite was true.

Based on the previously reported self-advantage for synchronization, it was anticipated that when agent identity was unknown, participants should demonstrate superior synchronization performance with recordings derived from their own movements when compared to those derived from another person (i.e., agent-self advantage). For this reason, post-perturbation differences in recovery rates were also assessed to see whether participants would show faster recovery following a tempo change when they kept synchrony with their own movements versus the movements of another person. The second prediction was that agency-belief would modulate synchronization behaviour such that if a participant believed the stimulus agent was themselves, this should yield better performance than when they believed this agent to be another person. However, it was predicted that this effect would not be entirely incognizant of the true identity of the agent and, instead, the possibility that a self-agency advantage might take precedence over a self-belief manipulation was left open. Thus, for example, a false self-belief effect (i.e., being told that the agent is yourself when actually it is someone else) might be stronger than a correct other-belief, but this might still be weaker than a false other-belief (i.e., being told that the agent is someone else when actually it is yourself), which in turn might be weaker than a correct self-belief effect. Therefore, the hypotheses underscored an interplay of both top-down (belief) and bottom-up stimulus-driven (agent) information in influencing interpersonal synchronization.

This study differed significantly from those previous reported. Firstly, belief surrounding agent identity was manipulated along self versus other dimensions (i.e., both biological), in contrast to the previously reported biological versus non-biological belief manipulations (Liepelt & Brass, 2010; Stanley et al., 2007). Secondly, whereas agency-belief has previously been manipulated in a between-participants interference or passive observation paradigm (Liepelt & Brass 2010, Stanley et al., 2007; Stanley et al., 2010), this current study was implemented as a within-participants design using synchronization criteria rather than interference as the dependent measure. Lastly, whilst the stimuli (viewed stereoscopically with 3D goggles) were still relatively ambiguous due to the point-light methodology employed, they were certainly less ambiguous than motion of a single dot (Stanley et al., 2007) and possessed richer kinematic information than the 2D images commonly used in motor priming experiments (Liepelt & Brass, 2000). In effect, this present study aimed to merge the self-advantage evidence reported from synchronization literature (Keller et al., 2007) with the animacy belief (regardless of true agency) effects reported from interference studies (Stanley et al., 2007). The theoretical value of connecting both these areas of research was seen as a principal goal of this study, alongside also providing more detailed investigation into the attention and gating mechanisms for top-down modulation of movement production as promoted by Liepelt and Brass (2010).

3.2 Method

3.2.1 Participants

Twelve right-handed participants (6 female) with normal or corrected-to-normal vision were recruited from the University of Birmingham. Average age was 23.75 years (*SD* = 2.63). Participants were naïve to the purpose of the study and were remunerated with a choice of research credits or £20 cash. Prior to participation, each volunteer provided informed consent.

3.2.2 Apparatus and Materials

3.2.2.1 Motion tracking equipment

To create stimuli and to record synchronization performance, a Qualysis (Qualysis, Sweden) motion capture system was utilized which comprised a series of 12 cameras that emit infrared light. When this infrared light hits the shiny surface of a passive reflective marker, it is reflected back to the camera (Figure 3.1), allowing the marker's movement in 3D space to be tracked through a process of triangulation, so long as the marker is within the field of view of at least two cameras. 52 spherical reflective markers (radius = 2 cm) were used to record whole-body movement in a highly accurate (spatial resolution in the range of 1 mm) and unconstrained manner. Figure 3.2 displays the arrangement of markers, which were chosen to monitor the key limb segments, head and trunk, loosely based on the point-light configurations previously published by Jokisch, Daum and Troje (2006). Markers were sampled at 200 Hz.

Figure 3.1 The resting position of the upward movement. The right image is an infrared photograph of the model showing the reflective markers in a point-light effect.

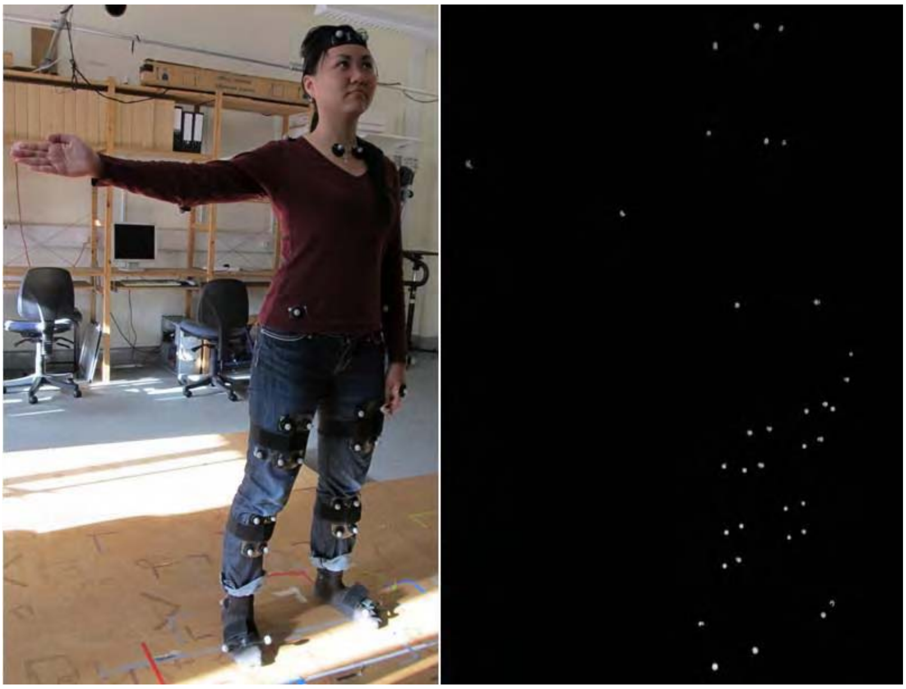
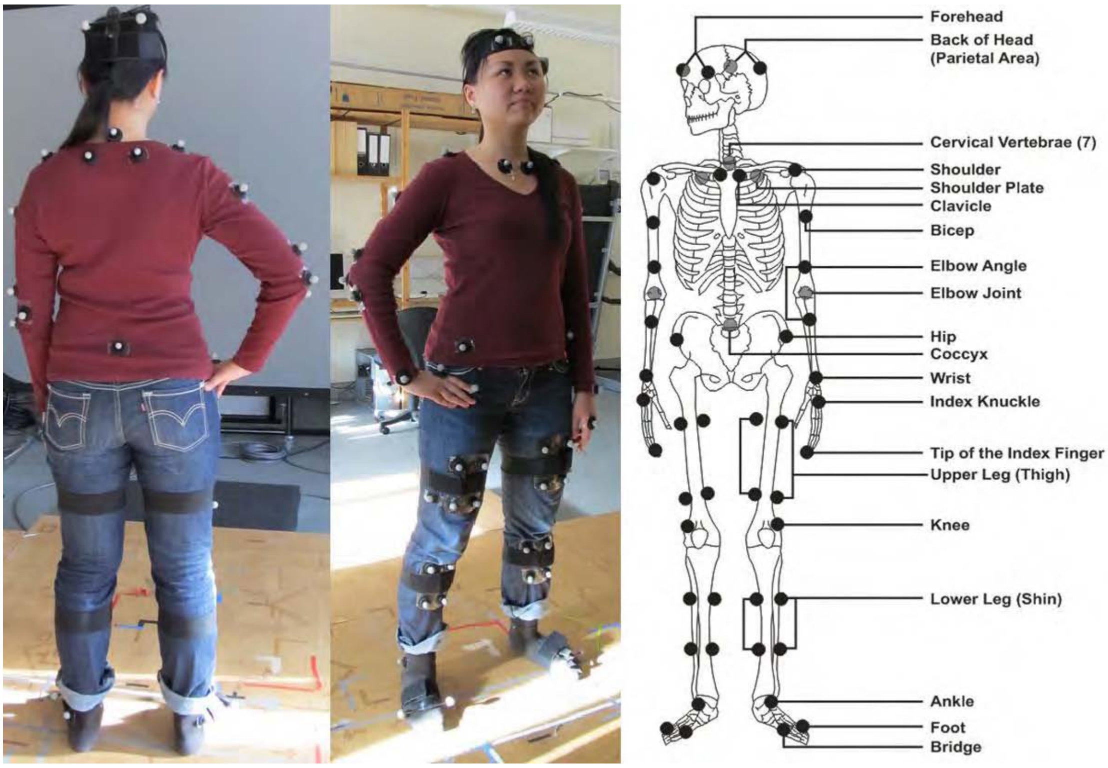


Figure 3.2 The arrangement of the 52 marker system.



3.2.2.2 Point-light stimuli

Motion recordings from the first session were exported to Matlab (Mathworks, MA) to create point-light stimuli for the later synchronization sessions. The experimenters watched the original recordings and selected one clean upwards arm movement for stimulus construction. The section of the recording representing the start to end time of this upward chosen movement (Figure 3.3) was then repeated to create a stimulus clip of ten identical up-and-down movements (thus 20 movements total). Importantly, the downward component of movement in the stimuli was actually the reversed playback of the upwards movement. This enabled the temporal and spatial aspects of upwards and downwards movements in the stimuli to be identical. The displayed markers were held motionless for a period of 0.5 s (100 frames) at the start (Figure 3.3, left image) and end (Figure 3.3, right image) of the series of ten upward movements, to represent the rest periods in the original recording.

A feature of this stimulus construction was that the playback tempo of individual movements could be controlled to create stimuli of different tempo as well as to create tempo perturbations within a recording. To this end, for each participant, 18 trials varying in tempo were produced and these were classified into three trial types (Table 3.1). 'Unperturbed' trials were those in which the tempo remained constant for all twenty (up and down) movements. In total, six unperturbed tempos were used ranging from slow (e.g., 1350 ms per upward/downward movement) to fast (e.g., 950 ms per upward/downward movement). The second trial type was 'perturbed fast-to-slow (F2S)', in which the tempo reduced by 350 ms from a fast frequency to a slower one (6 trials). The third trial type, 'perturbed slow-to-fast (S2F)', was the opposite of a perturbed F2S trial, as tempo increased by 350 ms per upward/downward movement from a low frequency to a higher one (6 trials). For both of these perturbed trial types, the change in tempo was abrupt and occurred on the 9th or 11th (upwards) movement in the sequence. These two variable onsets of tempo change for perturbed trials were to prevent participants from being able to predict with certainty when a tempo change might occur. Moreover, the purpose of different trial types was firstly to ensure that participants attended to the visual display throughout the whole trial and secondly to also assess any differences in the post-perturbation recovery rates that might be linked to the agency or belief manipulation. Trial length ranged from 29 s to 37s. To create smooth tempo changes in the stimuli recordings cubic-spline interpolation was used.

To facilitate synchronization, stimuli were presented to participants as though from a specular (mirror-like) viewpoint. It was felt this would prove advantageous for synchronization, by allowing participants to exploit congruent information from both spatial and motor representations, whilst also avoiding uncertainties still debated about specular and anatomical preferences in imitation (see Bekkering, Wohlschläger, & Gattis, 2000; Belopolsky, Olivers, & Theeuwes, 2008).

Figure 3.3: Start (left image) and end (right image) positions of the upwards movement

3.2.2.3 3D projection system

A 3D projection unit allowed the point-light stimuli relayed from the computer to be viewed in 3D when wearing 3D goggles (Infitec, Germany). Stimuli were projected on to a large screen (2.50 × 1.90 m) located 180 cm in front of where the participant stood.

Table 3.1 Stimuli tempos

Stimuli Types			
Trial type	**Unperturbed**	**Perturbed F2S**	**Perturbed S2F**
1	**950 ms**	**1000-1350 ms**	**1350-1000 ms**
2	**1000 ms**	**950-1300 ms**	**1300-950 ms**
3	**1050 ms**	**1050-1400**	**1400-1050 ms**
4	**1250 ms**	**1000-1350 ms**	**1350-1000 ms**
5	**1300 ms**	**950-1300 ms**	**1300-950 ms**
6	**1350 ms**	**1050-1400 ms**	**1400-1050 ms**

Session 2: 18 agent-self stimuli & 18 agent-other stimuli = 36 trials

Session 3: 36 agent-self stimuli (18 self-belief, 18 other-belief) & 36 agent-other stimuli (18 self-belief, 18 other-belief) = 72 trials

Tempo change at movement 9 **Tempo change at movement 11**

3.2.3 Design and Procedure

Upon first arrival and after having read instructions, participants were measured for height and tested for stereopsis. On a red-green stereo display, participants watched a short clip using 3D glasses and self-reported whether they could in fact see in 3D. After this and at the beginning of each subsequent session, participants removed their shoes and were fitted with 52 reflective markers using adhesive tape and Velcro strips (Figure 3.1, 3.2). In total, participants attended three sessions.

3.2.3.1 Session 1: Stimulus recording session

The original recording session was described to participants as a practice session designed to test their suitability for future sessions. Participants were asked to repeatedly perform a simple arm movement, which involved moving their right arm from a holding position at the hip, up and outwards to an outstretched position at roughly shoulder height (Figures 3.1, 3.3), holding there for short period, before finally moving back to the original position where they would again hold for another short period. Participants were asked to keep the rest of their body as still as possible and to maintain their left hand held at a fixed position loosely against the left side of their body. This movement was chosen as it was both novel and easy to perform but also because, unlike say a swinging action, it had no immediate behavioural connotation (e.g., tennis). The experimenter demonstrated the movement to the participant, who then practised under guidance for a few minutes with a metronome set at 140 beats per minute used to perfect the timing of the actions and the rest periods, thus ensuring similarity in timing (1400 ms per movement) across all participants. Finally, two 35 s recordings were then tracked and recorded using Qualysis.

The recordings from this session were used to create the point-light stimuli used in the synchronization sessions. In addition to the creation of each participant's stimuli, stimuli were also created for a gender-matched participant. Where possible, each participant was matched to another physically similar participant (e.g., on the basis of physique, height), but in five cases, additional appropriately selected volunteers were recruited to provide stimuli recordings only.

3.2.3.2 Session 2: Synchronizing to Unknown Agents (Uninduced Belief)

After an average of five days from Session 1, participants returned for the first synchronization session. Participants wore 3D glasses throughout.

Participants were informed they would be performing similar movements to those they had practiced in the first session but, crucially, they would now have to synchronize their movements to those of the agent in the display. The agent in the display was scaled to approximately two-thirds of the size of the participant. Participants were asked to synchronize with the overall (spatial and temporal aspects of) movement and not just to ensure they reached the endpoints at the same time. No explicit information was given about who they were synchronizing with. In total, participants performed 36 trials. Half of these trials involved the participant synchronizing with stimuli generated from their own recordings, whilst the other half of trials involved the participant synchronizing with stimuli created from the person to whom they were matched. Agency (self, other) was randomized across trials. A short break was set halfway through the session, but participants were free to take other rest breaks if they wished.

3.2.3.3 Session 3: Induced Belief Synchronization

An average of three days after Session 2, participants returned for the final session, which consisted of 72 trials. To induce belief about the agent they synchronized to, experimenters verbally indicated to the participant whether they would be watching themselves or another agent. In addition, the virtual computer desktop was projected onto the screen, allowing the participant to view the experimenter pressing 'play' on the stimulus video, which was labelled with either their name or the gender-matched name of another person. This manipulation was designed to produce four belief conditions. The first was a case in which the participant watched their own movements and were truthfully informed these were their movements (correct agent-self belief, 18 trials). The second was a condition in which the participant watched their own movements but were falsely informed these were another person's movements (false agent-other belief, 18 trials). The third case consisted of a situation where the participant watched another person's movements but they were falsely informed that these were their own movement (false agent-self belief, 18 trials). In the final belief condition, participants watched the other person's movements and were correctly informed of the true agency of the stimuli (correct agent-other belief, 18 trials). Belief conditions were ordered in a randomized manner across trials.

At the end of this session, prior to being debriefed, participants were asked to take a half hour break before returning to complete two short tasks. The first of these was a discrimination task (27 trials) in which participants viewed two clips in succession of one another and had to indicate whether the clips were identical or not. Each clip consisted of the first two movements from a 1000 ms unperturbed stimulus file taken from the participant, the person they had been matched (i.e., paired) to and a third previously unseen agent, taken from one of the other participants in the study. For each agent (self, other, new), there were 3 repetitions of each possibility: identical (3), different - paired other (3), different - new other or different-self (3) depending on agent. The second task, which served as a self-recognition test, comprised 9 trials in which participants again watched two movements from a stimulus video as used in the discrimination task; they were asked to specify after each of the nine clips whether they thought the person they had seen was themselves or not (3 self, 3 paired-other, 3 new-other).

3.3 Dependent measures

Sensorimotor synchronization (SMS) is a term used to describe the rhythmic (temporal) coordination of perception and action (Repp, 2005). The task in this study expressly required participants to synchronize their own motor output to the movements they perceived in the external visual display and hence represented a form of SMS.

Much of the literature examining SMS involves tapping tasks in which participants must coordinate an action (usually a finger tap) to an external cue (such as an auditory metronome). A popular method of quantifying SMS performance is to measure the mean asynchrony (MA), that is the asynchrony between the onset of the stimulus event (e.g., metronome tone) and the time occurrence of the participant's action. Quite often in SMS tapping tasks, there exists an anticipation tendency known as the negative mean asynchrony

(NMA), whereby taps tend to precede the stimulus event (see Aschersleben, 2002). The NMA phenomenon is far more pronounced in untrained participants compared to skilled musicians, who may even lack a NMA (Aschersleben, 2002). Further to this, tapping tasks also commonly employ another measure used to quantify performance quality. In this second measure, interonset intervals (IOI) between two stimulus events are compared against the intertap-interval (ITI) in actions produced in response to the stimulus. This effectively computes the differences in phase durations of the stimulus event and the participant's own movements. This was termed the inter-movement-interval discrepancy (IMI) in the current study. The variability of asynchronies and IMIs in an SMS task is also a valuable gauge of a participant's synchronization skill, as exemplified by improved performance on both of these measures for skilled musicians (Repp, 2005). Accordingly, these measured were also investigated.

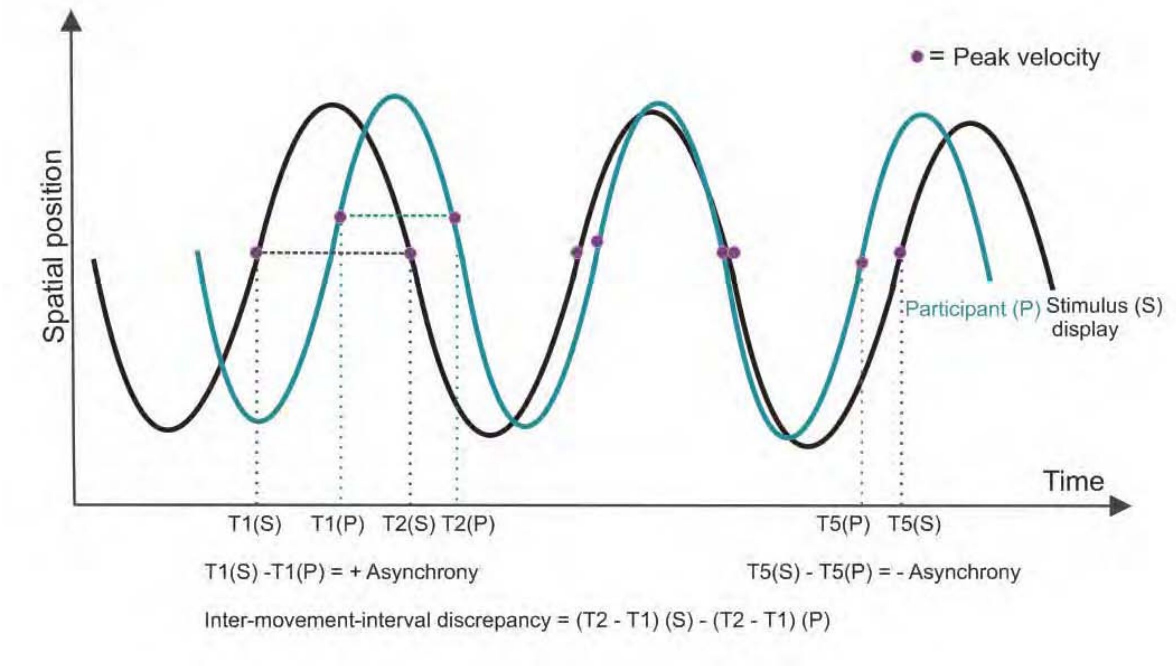
The differences in the peak velocities of the stimulus display (i.e., the 'metronome') and the participant's movement were used as the movement events from which asynchronies and IMI were calculated. Therefore, an asynchrony represented the difference in time between the stimulus's and participant's peak velocities for a given movement. Similarly, an IMI was the time discrepancy between the time difference of the stimulus's peak velocities for two movements (upward and downwards) and the time difference of the participant's peak velocities for the equivalent two movements (see Figure 3.4). Thus:

Asynchrony: Stimulus T1 - Participant T1

IMI: Stimulus (T2 -T1) - Participant (T2-T1)

A custom built Matlab (Mathworks, MA) script was used to detect peak velocities in each movement of the index fingertip marker of the right hand of both stimuli recordings and experimental recordings. The spatial position (i.e., trajectory) of this fingertip marker was subsequently differentiated to acquire the velocity profile of the movement. As the first movement was always upwards, it was known that the first and every other odd numbered peak velocity detected was that of an upwards movement. Conversely, every even numbered peak (starting from the second peak detected) was known to be a downwards movement. Thus, each dependent measure computed for each partitioned movement could then be averaged across equivalent movements (upwards or downwards) in the trial to give an overall indicator of the performance for that trial. The first movement from each trial was discarded from analysis.

Figure 3.4 Schematic representation of the stimulus-participant asynchronies and inter-movement-interval discrepancies.



3.4 Results

For Session 2 and 3 respectively, 3.70% and 2.78% of data were excluded either because the participant skipped a movement or because recordings were low in quality, leading to peak detection problems (Table 3.2).

Table 3.2 Summary of excluded trials

Session 2	Agency condition			**Session 3**	Belief condition				
Trial Type	**Agent self**	**Agent other**	Trials excluded per trial type	Trial Type	**Agent self, belief self**	**Agent self, belief other**	**Agent other, belief self**	**Agent other, belief other**	Trials excluded per trial type
Perturbed F2S	4	0	**4**	**Perturbed F2S**	5	2	0	1	**8**
Perturbed S2F	3	6	**9**	**Perturbed S2F**	2	1	0	2	**5**
Unperturbed	2	1	**3**	**Unperturbed**	6	3	0	2	**11**
Trials excluded per agency condition	**9**	**7**	**16**	Trials excluded per belief condition	**13**	**6**	**0**	**5**	**24**
Overall data excluded	**16/432 trials (3.70%)**			**Overall data excluded**	**24/864 trials (2.78%)**				

3.4.1 Analyses of Dependent Variables

In total, five dependent variables (DVs) were examined. These were: (1) the mean asynchrony (MA), (2) the standard deviation (i.e., variability) of the asynchrony (SDA) (3) the absolute asynchrony (AA), (4) the absolute mean inter-movement-interval discrepancy (IMI), and (5) the standard deviation of the inter-movement-interval discrepancy (SDIMI) (refer to Section 3.3 for a description of DVs). Each DV was subjected to a separate within-participants repeated measures ANOVA. To prevent order effects from influencing results, Session 2 and Session 3 were examined independently. For Session 2, the analysis was a 3 (trial type: unperturbed, perturbed F2S, perturbed S2F) × 2 (agency: self, other) × 2 (movement direction: upwards, downwards) ANOVA. For Session 3, an ANOVA was performed with the aforementioned factors plus the additional two-level factor of belief (self, other). Nonsignificant results ($p > .05$) are not discussed. All significant interactions are reported, however, only significant interactions involving belief or agency were examined further using simple effects analyses. All error bars represent ±1 standard error of the mean.

3.4.1.1 The mean asynchrony (MA)

3.4.1.1.1 Session 2

The ANOVA revealed significant main effects of trial type, $F(1.33, 14.62) = 6.79$, $p < .05$, $\eta_p^2 = .38$ (Figure 3.5), agency, $F(1,11) = 5.11$, $p < .05$, $\eta_p^2 = .32$ (Figure 3.6), and movement direction, $F(1,11) = 30.94$, $p < .001$, $\eta_p^2 = .74$ (Figure 3.7). Average MA was 6.3 ms for unperturbed trials, 28.7 ms for perturbed F2S trials and 33.5 ms for perturbed S2F trials. The only reliable significant differences exposed by Bonferroni pairwise comparisons were smaller MAs for unperturbed trials compared to perturbed F2S, ($p < .01$) and S2F, ($p < .05$) trials. Average MA for agent-self (30.3 *ms*) was significantly larger than that of agent-other (15.4 *ms*). Additionally, average MA for upwards movement was significantly larger (59.0 *ms*) than that of downwards movement (-13.3 *ms*). On average, upwards movements trailed behind (positive MAs) the stimulus display whilst downwards movements were ahead (negative MAs) of the stimulus display.

The interaction between trial type and agency was also significant, $F(2,22) = 5.74$, $p < .05$, $\eta_p^2 = .34$ (Figure 3.8), as too was a three-way interaction between trial type, agency and movement direction, $F(2,22) = 3.86$, $p < .05$, $\eta_p^2 = .26$ (Figure 3.9).

For the interaction between agency and trial type, significant differences in agency were found for unperturbed trials only, $F(1,11) = 9.28$, $p < .05$, $\eta_p^2 = .46$. Here, average MA values indicated that participants were further behind the stimulus during agent-self trials (25.4 *ms*) than during agent-other trials (-12.8 *ms*). Equally, significant differences in trial type were observed in the agent-other condition only, $F(2,10) = 8.50$, $p < .01$, $\eta_p^2 = .63$. In the agent-other condition, average MA values for performance during unperturbed trials (-12.8 *ms*) were further ahead of the stimulus than those of F2S (27.3 *ms*; $p < .01$) and S2F (31.7 *ms*; $p < .05$) trials, which both tended to lag behind the stimulus.

Interpretation of the three-way interaction between agency, trial type and movement direction using simple effects analyses revealed an agent effect on upwards movements during unperturbed trials, $F(1,11) = 24.75$, $p < .001$, $\eta_p^2 = .69$. Agent-self trials (61.9 *ms*) in this condition were found to have MAs that trailed significantly further behind the stimulus display than MAs during agent-other (14.3 *ms*) trials in the equivalent condition.

As noted previously, trial type differences were found when comparing unperturbed trials to both perturbed (F2S & S2F) conditions during agent-other trials only. The three-way interaction further established these differences to be specific to upwards movements only. MAs for unperturbed trials (14.3 *ms*) in the agent-other upwards-movement condition were closer in time to the stimulus display than MAs for F2S, (67.9 *ms*; $p < .01$) and S2F, (74.7 *ms*; $p < .05$) trials in the equivalent condition. The analyses also uncovered significant movement direction effects for all trial types in both agent conditions (all at least $p < .05$). MAs for upwards movements were on average larger and further behind the stimulus display than the MAs seen for downwards movements, which tended to be shorter and slightly ahead of the stimulus display. Only one exception was noted, which was for unperturbed trials in the agent-other condition. Here MAs for downwards movements were significantly larger, though still farther ahead of the stimulus display, than upwards movements, which were shorter and slightly behind the stimulus display.

Figure 3.5 Session 2, mean asynchrony (MA): The main effect of trial type.

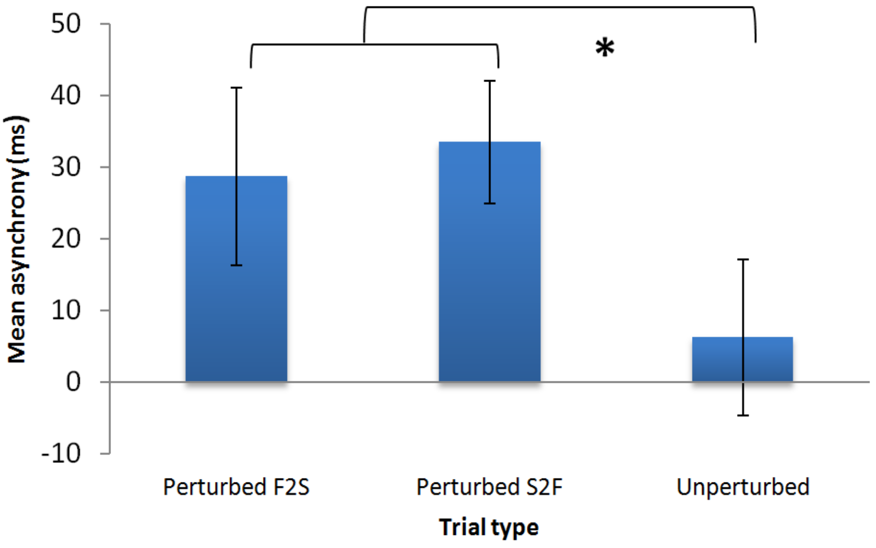


Figure 3.6 Session 2, mean asynchrony (MA): The main effect of agency.

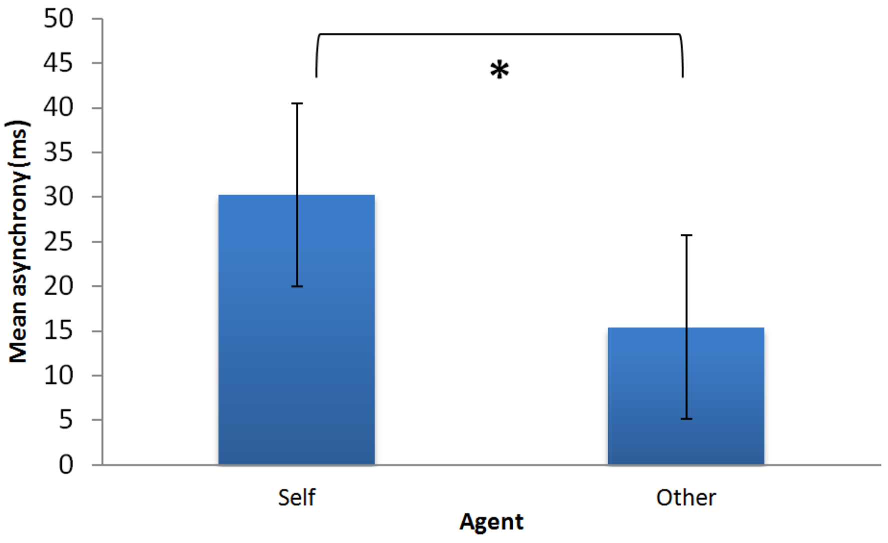


Figure 3.7 Session 2, mean asynchrony (MA): The main effect of movement direction.

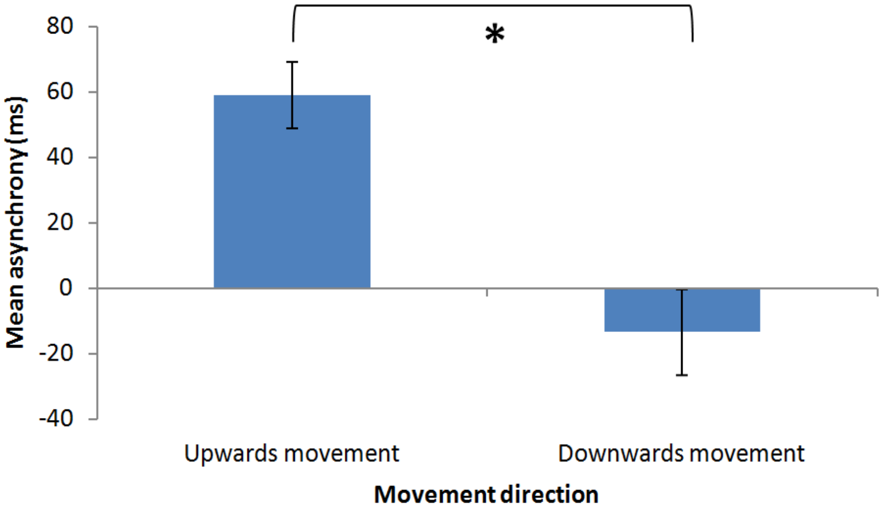


Figure 3.8 Session 2, mean asynchrony (MA): The interaction between agency and trial type.

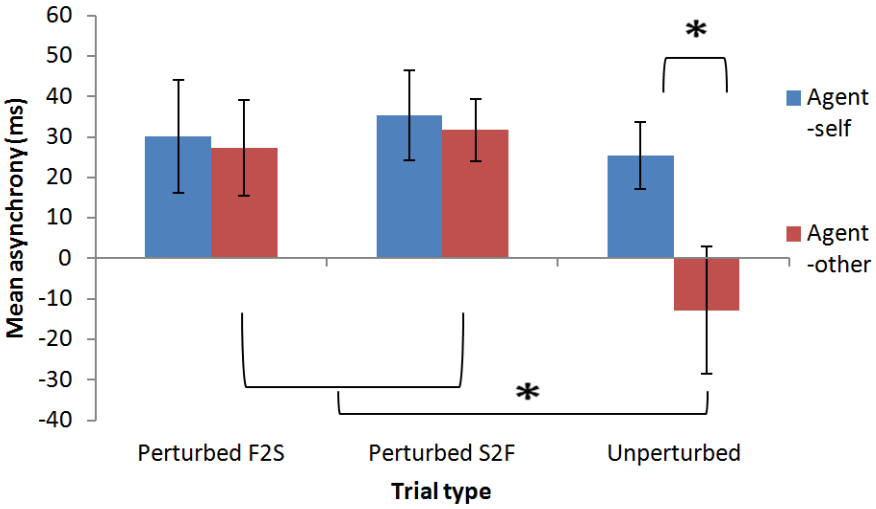
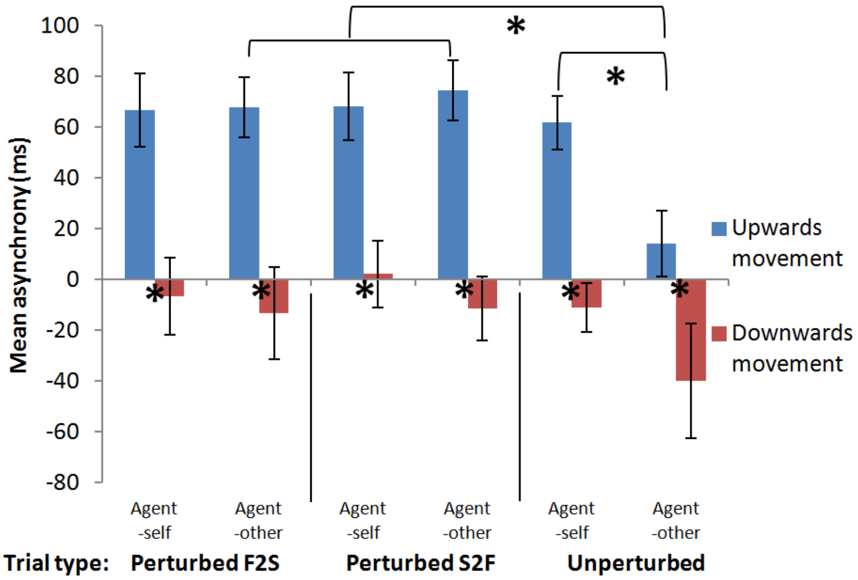


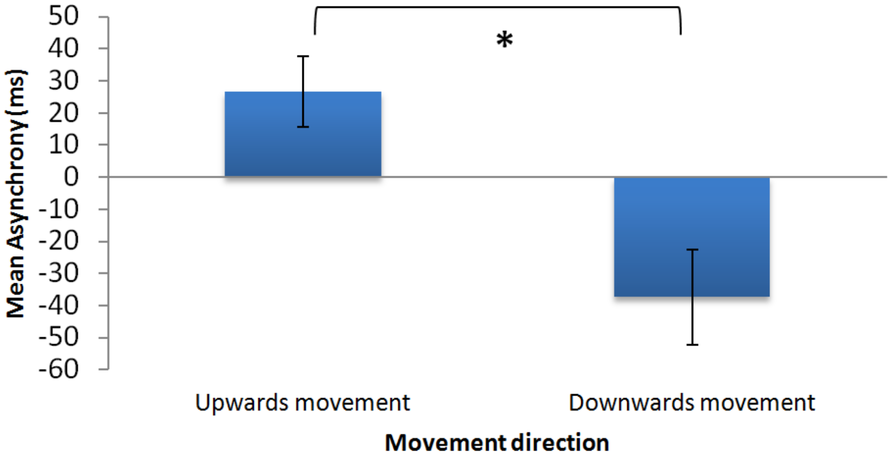
Figure 3.9 Session 2, mean asynchrony (MA): The three-way interaction between agency, trial type and movement direction.



3.4.1.1.2 Session 3

The ANOVA revealed a significant main effect of movement direction $F(1,11) = 13.76$, $p < .01$, $\eta_p^2 = .56$ (Figure 3.10). Average MAs for upwards movements (26.5 *ms*) were significantly smaller and further behind the stimulus display than MAs of downwards movement (-37.3 *ms*), which by comparison were ahead of the stimulus display.

Figure 3.10 Session 3, mean asynchrony (MA): The main effect of movement direction.



3.4.1.2 The standard deviation of the asynchrony (SDA)

3.4.1.2.1 Session 2

The ANOVA revealed a significant main effect of movement direction $F(1,11) = 68.34$, $p < .001$, $\eta_p^2 = .86$ (Figure 3.11). Average asynchronies for upwards movements were significantly less variable (50.6 *ms*) than those of downwards movements (65.9 *ms*). A three-way interaction between trial type, agency and movement direction $F(2,22) = 3.88$, $p < .05$, $\eta_p^2 = .26$ was also significant (Figure 3.12).

Simple effects analyses performed on this interaction revealed no significant agent effects on trial type or movement direction, nor were there any significant trial type effects on agency or movement direction ($p > .05$). On the other hand, significant movement direction effects were noted for all trial types during both agent conditions (all at least $p < .05$). The SDA measure consistently showed that upwards movements experienced on average far less asynchrony variability than downwards movements when synchronizing to the stimulus display.

Figure 3.11 Session 2, the variability of asynchrony (SDA): The main effect of movement direction.

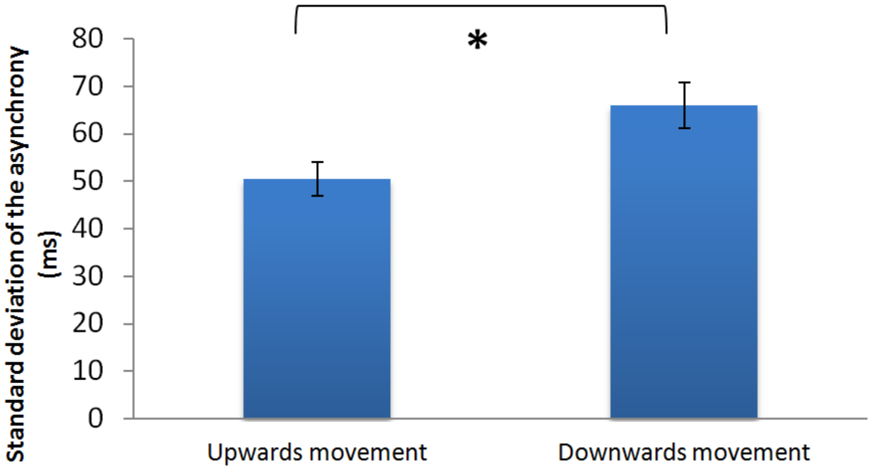
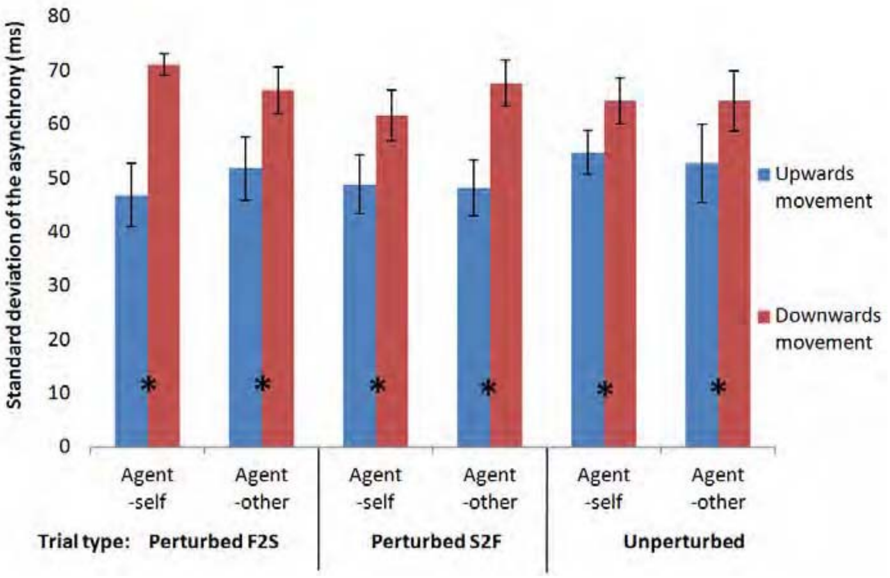


Figure 3.12 Session 2, the variability of asynchrony (SDA): The three-way interaction between, agency, trial type and movement direction.



3.4.1.2.2 Session 3

The ANOVA identified significant main effects of belief $F(1,11) = 8.26$, $p < .05$, $\eta_p^2 = .43$ (Figure 3.13) and movement direction $F(1,11) = 24.50$, $p < .001$, $\eta_p^2 = .69$ (Figure 3.14). Average SDAs for self-belief trials (57.2 *ms*) were significantly smaller than those of other-belief trials (63.8 *ms*). Hence, performance was less variable during self-belief trials compared to other-belief trials. Furthermore, average SDAs for upwards movements (55.0 *ms*) were significantly smaller (and hence performance less variable), than those of downwards movements (66.0 *ms*).

Figure 3.13 Session 3, the variability of asynchrony (SDA): The main effect of belief.

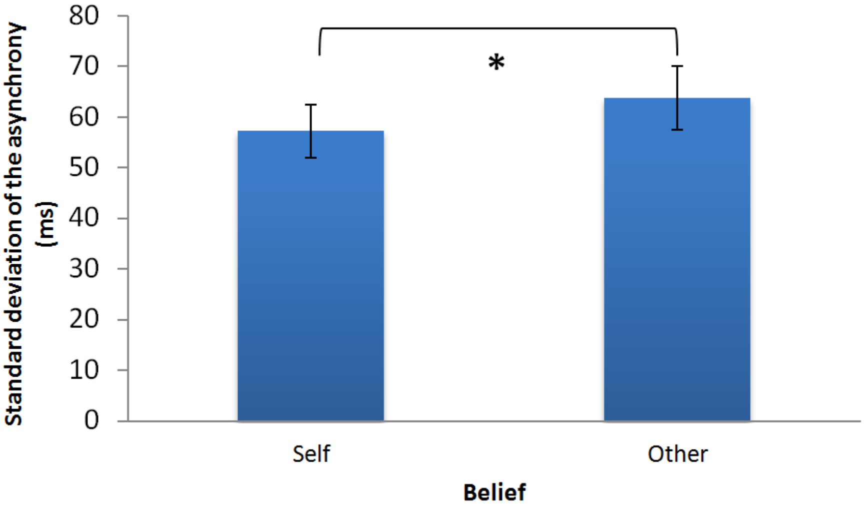
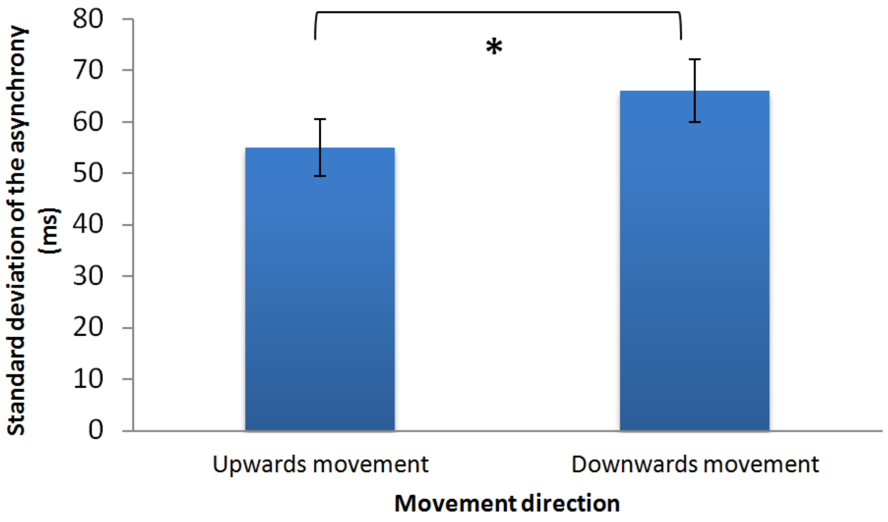


Figure 3.14 Session 3, the variability of asynchrony (SDA): The main effect of movement direction.

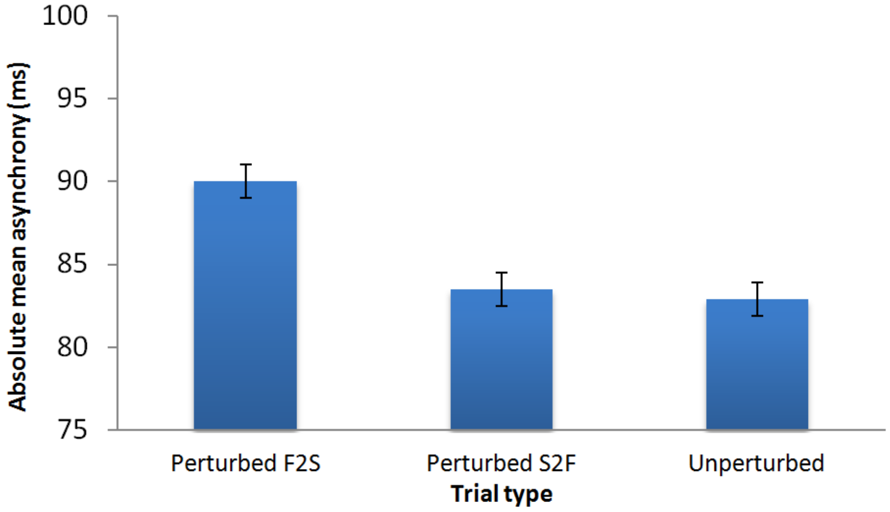


3.4.1.3 The absolute mean asynchrony (AA)

3.4.1.3.1 Session 2

The ANOVA revealed significant main effects of trial type $F(2,22) = 3.97$, $p < .05$, $\eta_p^2 = .27$ (Figure 3.15). Average AA was 82.9 ms for unperturbed trials, 90.0 ms for F2S trials and 83.5 ms for S2F trials. However, Bonferroni pairwise comparisons unveiled no reliable differences across trials types (p > .05).

Figure 3.15 Session 2, absolute mean asynchrony (AA): The main effect of trial type.



3.4.1.3.2 Session 3

No significant effects were found for AA here.

3.4.1.4 The absolute mean inter-movement-interval discrepancy (IMI)

3.4.1.4.1 Session 2

The ANOVA identified significant main effects of trial type $F(2,22) = 8.39$, $p < .01$, $\eta_p^2 = .43$ (Figure 3.16) and movement direction $F(1,11) = 22.60$, $p < .01$, $\eta_p^2 = .67$ (Figure 3.17). The average IMI was 81.0 ms for unperturbed trials, 93.3 ms for F2S trials and 75.8 ms for S2F trials. Pairwise comparisons established only one reliable difference between trial types, which indicated significantly smaller IMIs for perturbed S2F trials compared against perturbed F2S trials (p < .01). On average, the stimulus-participant (i.e., observed-executed) discrepancy in phase duration (as measured using IMIs) was smaller for upwards movements (78.5 *ms*) compared to downwards movements (88.3 *ms*).

The interaction between trial type and movement direction was also significant *F*(2,22) = 4.35, $p < .05$, $\eta_p^2 = .28$, as too was a three-way interaction between trial type, agency and movement direction *F*(2,22) = 3.60, $p < .05$, $\eta_p^2 = .25$ (Figure 3.18). To interpret the agency component of this three-way interaction, simple effects analyses were employed.

There was no effect of agency on trial type or movement direction ($p > .05$). Trial type, however, showed an effect on both upwards *F*(2,10) = 10.60, $p < .01$, $\eta_p^2 = .68$ and downwards *F*(2,10) = 6.12, $p < .05$, $\eta_p^2 = .55$ movements during the agent-self condition. Significantly larger discrepancies between stimulus-participant phase durations were noted for upwards F2S trials (82.6 *ms*) compared against upwards S2F (58.5 *ms*) trials, when the agent in the display was the participant his/herself ($p < .01$). Equally, for downwards movements, significantly larger stimulus-participant duration differences were found for F2S (93.6 *ms*) compared against S2F (71.6 *ms*) trials ($p < .05$) in the agent-self condition. Finally, movement direction was also found to have a significant effect on almost all trial types during both agent conditions (all at least $p < .05$). The only exceptions were for unperturbed trials in the agent-self condition ($p = .05$) and F2S trials in the agent-other condition ($p > .05$). Significant cases consistently demonstrated smaller phase discrepancies for upwards compared to downwards movements, suggesting that participants were better at matching stimulus durations when producing upwards rather than downwards movements.

Figure 3.16 Session 2, absolute mean inter-movement-interval discrepancy (IMI): The main effect of trial type.

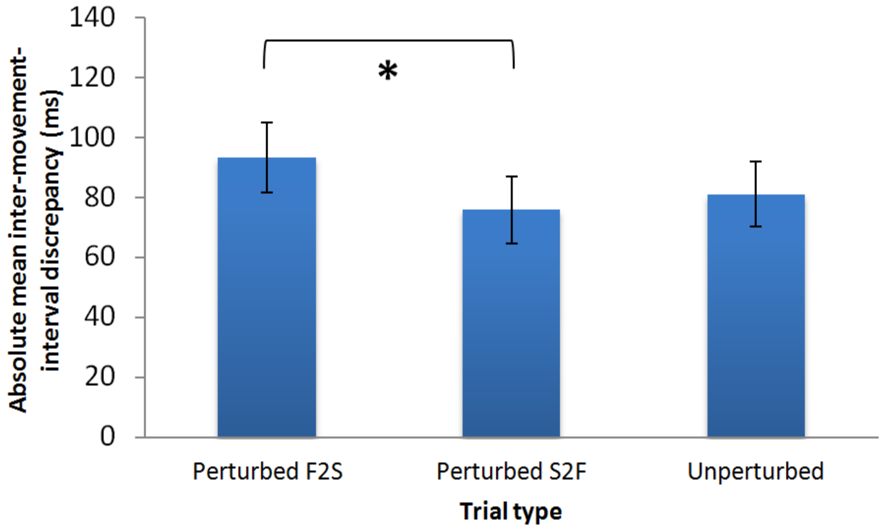


Figure 3.17 Session 2, absolute mean inter-movement-interval discrepancy (IMI): The main effect of movement direction.

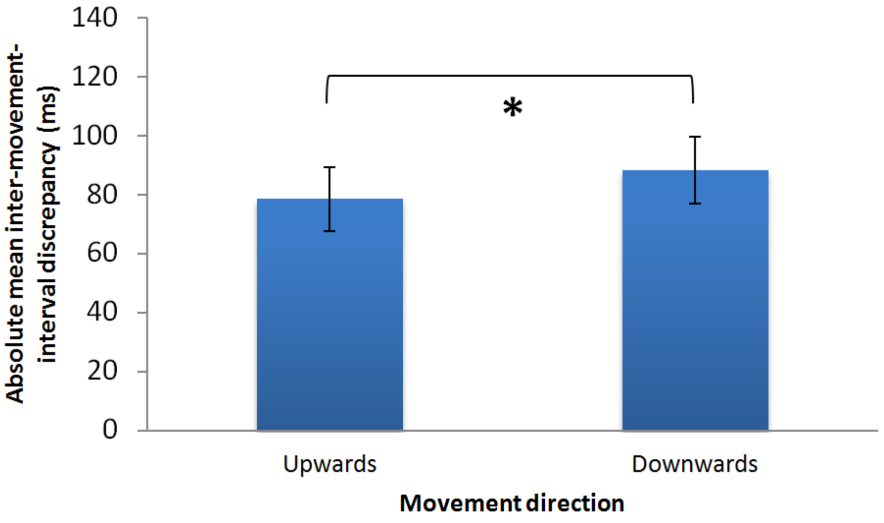
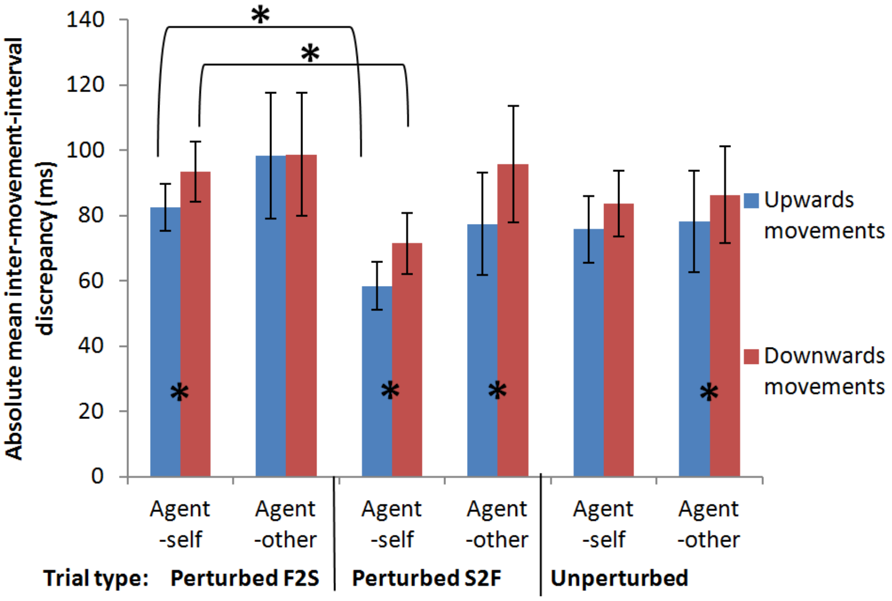


Figure 3.18 Session 2, absolute mean inter-movement-interval discrepancy (IMI): The three-way interaction between agency, trial type and movement direction.



3.4.1.4.2 Session 3

The ANOVA revealed significant main effects of belief $F(1,11) = 7.29$, $p < .05$, $\eta_p^2 = .40$ (Figure 3.19) and movement direction $F(1,11) = 22.55$, $p < .01$, $\eta_p^2 = .67$ (Figure 3.20). The stimulus-participant discrepancies in phase durations were significantly smaller for self-belief trials (77.8 *ms*) compared to other-belief trials (88.7 *ms*). Equally, IMIs of upwards movements were significantly smaller (78.8 *ms*) than IMIs of downwards movements (87.7 *ms*).

The interaction between belief and agency was also significant $F(1,11) = 5.84$, $p < .05$, $\eta_p^2 = .35$ (Figure 3.21). Significant differences in belief conditions only occurred for agent-other trials $F(1,11) = 13.46$, $p < .01$, $\eta_p^2 = .55$. Average stimulus-participant discrepancy values for self-belief trials (84.3 *ms*) indicated performance on these trials were more closely matched in phase duration to the display than trials in the other-belief condition (102.3 *ms*). There were no significant agent effects on belief ($p > .05$).

It is worth noting that the average IMIs obtained from the (uninduced belief) agent-other condition (89.1 *ms*) (Session 2) were comparable to the values obtained from Session 3 during agent-other self-belief trials (84.3 *ms*). On the other hand, IMIs during agent-other other-belief trials (102.3 *ms*) were at least superficially larger than those of agent-other in Session 2. This tentatively suggests that when synchronizing to biological motion derived from others, the explicit labelling of the stimulus as 'other' might be sufficient to reduce phase duration matching in performance.

Figure 3.19 Session 3, absolute mean inter-movement-interval discrepancy (IMI): The main effect of belief.

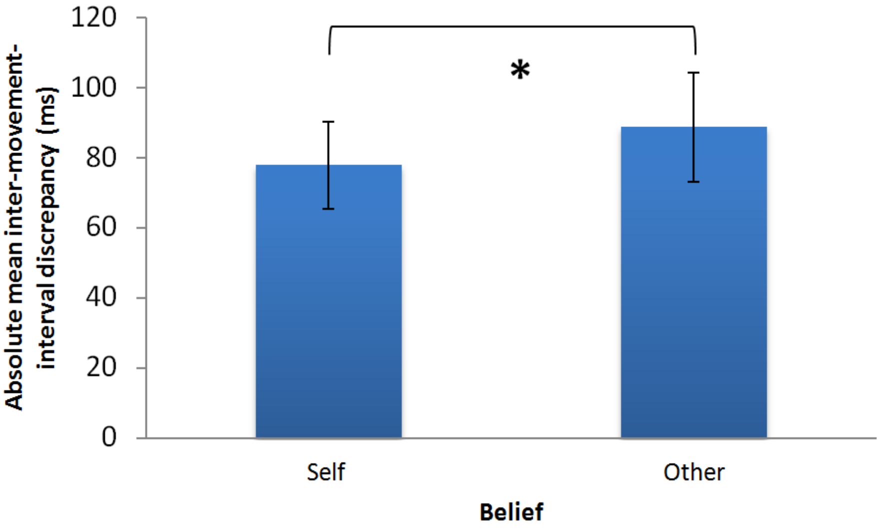


Figure 3.20 Session 3, absolute mean inter-movement-interval discrepancy (IMI): The main effect of movement direction.

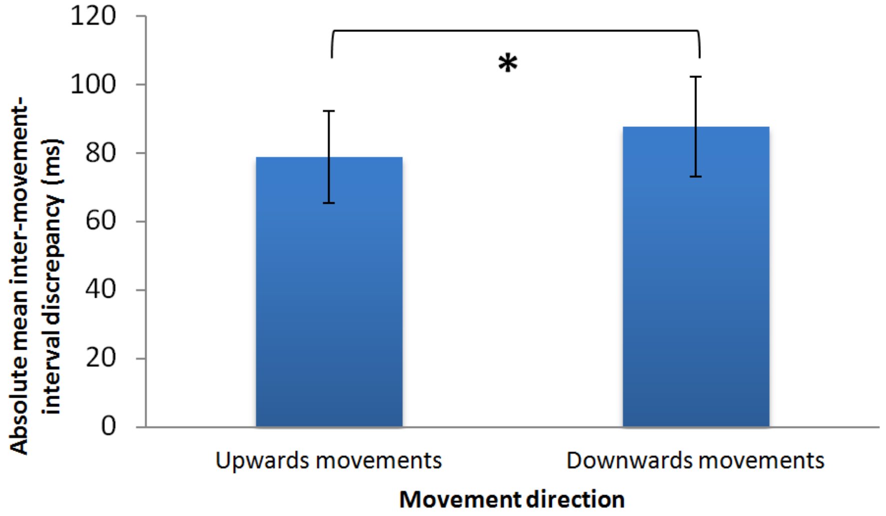
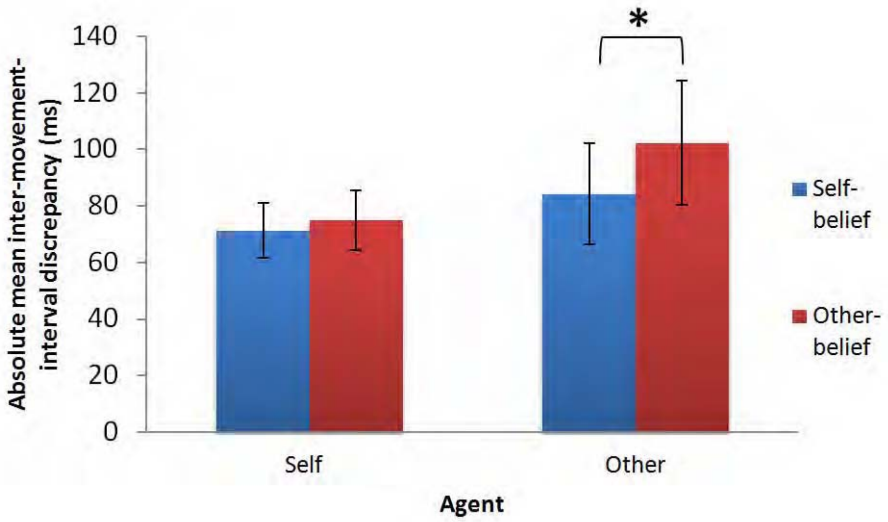


Figure 3.21 Session 3, absolute mean inter-movement-interval discrepancy (IMI): The interaction between agency and belief.



3.4.1.5 The standard deviation of the inter-movement interval discrepancy (SDIMI)

3.4.1.5.1 Session 2

The ANOVA identified significant main effects of trial type *F*(1.32, 14.54) = 5.15, $p < .05$, $\eta_p^2 = .32$ (Figure 3.22) and movement direction *F*(1, 11) = 18.94, $p < .01$, $\eta_p^2 = .63$ (Figure 3.23). The interaction between trial type and movement direction was also significant *F*(2, 22) = 5.59, $p < .05$, $\eta_p^2 = .34$. The average SDIMI was 72.5 ms for unperturbed trials, 93.3 ms for F2S trials and 75.8 ms for S2F trials. The stimulus-participant discrepancies in phase duration matching for S2F trials were significantly less variable than for perturbed F2S trials ($p < .01$). Less variability in the stimulus-participant phase discrepancies were also noted for upwards movements (77.3 *ms*) relative to downwards movements (83.8 *ms*).

Figure 3.22 Session 2, the variability of the inter-movement-interval discrepancy (SDIMI): The main effect of trial type.

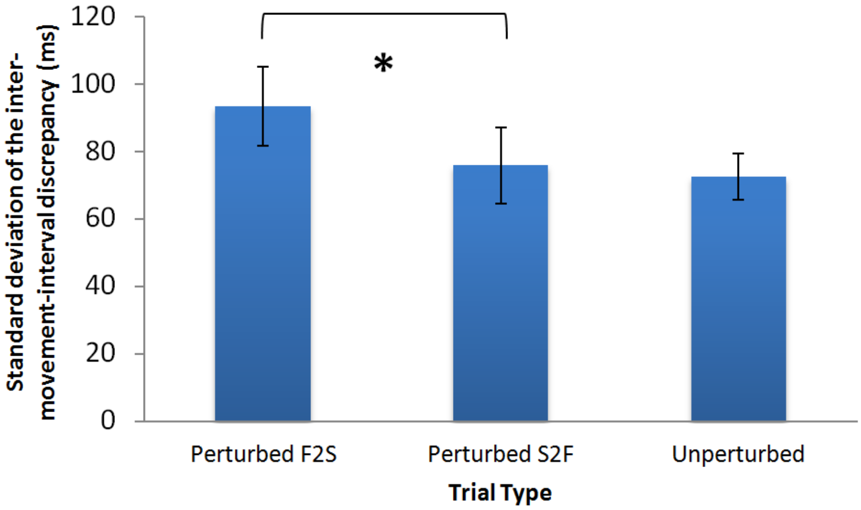
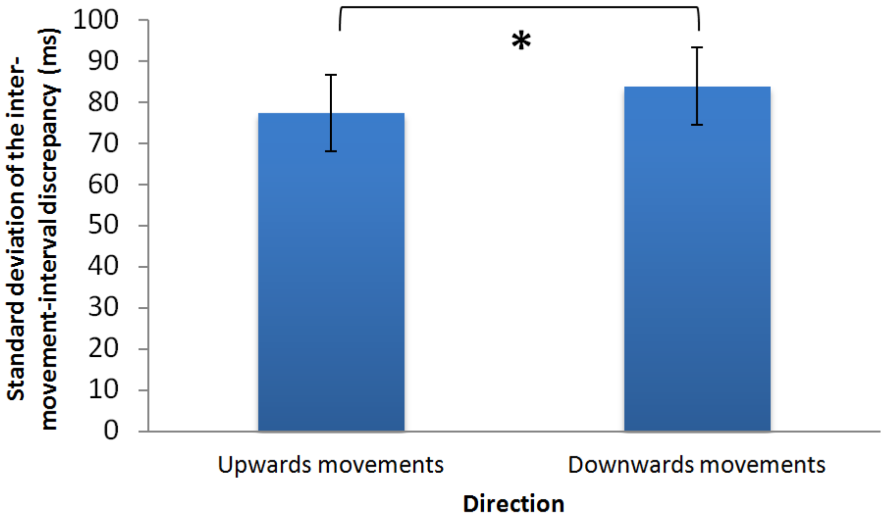


Figure 3.23 Session 2, the variability of the inter-movement-interval discrepancy (SDIMI): The main effect of movement direction.



3.4.1.5.2 Session 3

The ANOVA showed a significant main effect of belief $F(1,11) = 15.35$, $p < .01$, $\eta_p^2 = .58$ (Figure 3.24). The average SDIMI was significantly smaller for self-belief (67.1 *ms*) compared to other-belief (77.6 *ms*). This pointed to less variability in phase duration differences between observed and executed movements for self-belief trials compared to other-belief trials.

The interaction between belief and movement direction was also significant $F(1,11) = 11.17$, $p < .01$, $\eta_p^2 = .50$ (Figure 3.25). Significant differences across belief conditions were noted for upwards $F(1,11) = 17.44$, $p < .01$, $\eta_p^2 = .61$ and downwards $F(1,11) = 5.78$, $p < .05$, $\eta_p^2 = .34$ movement directions. During upwards movements, self-belief trials led to significantly smaller stimulus-participant phase duration discrepancies (65.9 *ms*) than compared to other-belief trials (81.5 *ms*). Likewise, for downwards movements, the average

SDIMI values for self-belief trials (68.4 *ms*) were less variable than those of other-belief trials (73.8 *ms*). There were no significant movement direction effects on belief ($p > .05$).

Figure 3.24 Session 3, the variability of the inter-movement-interval discrepancy (SDIMI): The main effect of belief.

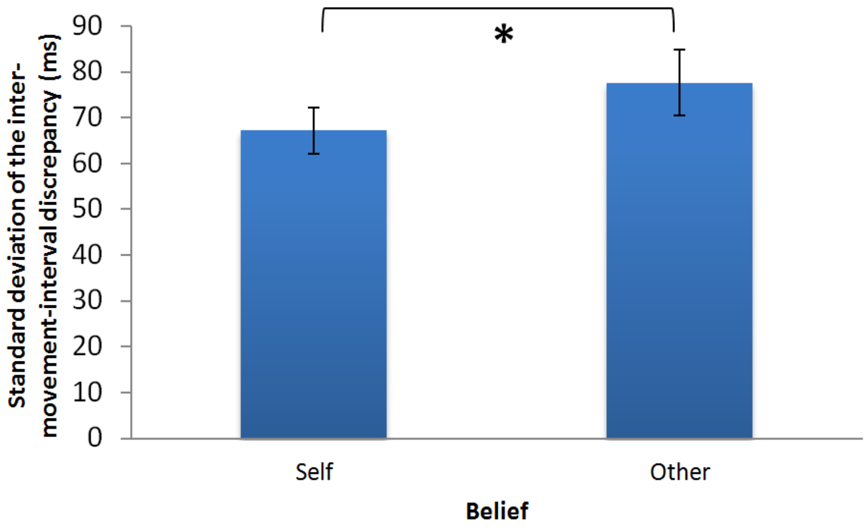
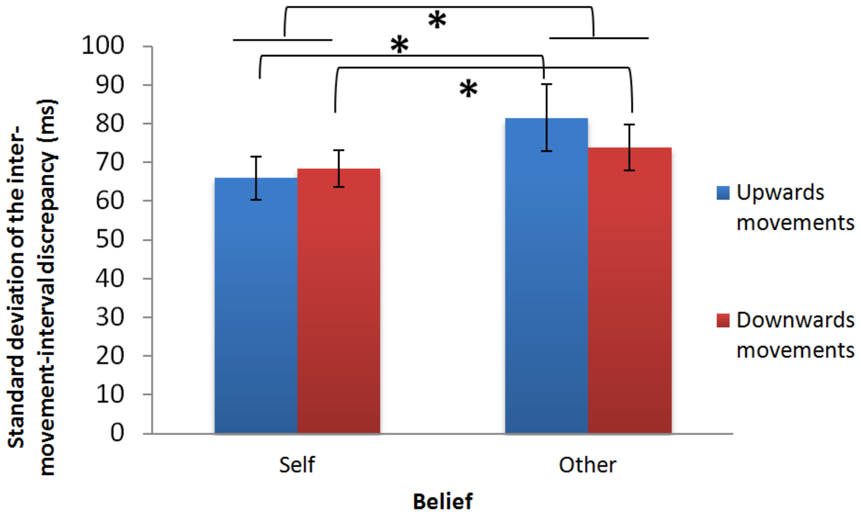


Figure 3.25 Session 3, the variability of the inter-movement-interval discrepancy (SDIMI): The interaction between belief and movement direction.



3.4.2 Further analyses

3.4.2.1 DV correlations with discrimination and self-recognition scores

Table 3.3 shows the scores obtained for each participant in the stimuli discrimination and self-recognition tasks. At the group level, two-tailed Pearson's correlations were conducted in which the percentage of correct responses for each participant in the discrimination task was correlated against their performance on each DV, averaged across all trials in which the agent in the stimulus had been the participant him/herself (agent-self).

A significant negative correlation was observed between participants' ability to discriminate stimuli and their performance during agent-self trials as measured using SDA, $r(12) = -.59$, $p < .05$ (Figure 3.26), IMI, $r(12) = -.72$, $p < .01$ (Figure 3.27) and SDIMI, $r(12) = -.66$, $p < .05$ (Figure 3.28). Correlations for MA and AA were not significant ($p > .05$). Similar correlations were performed for agent-other stimuli; however, no significant correlations were found.

Correlations between the percentage of correct scores in the self-recognition task and DV performance measures were also conducted. This yielded no significant correlations ($p > .05$). It is important to note, however, that these self-recognition correlations were based on data from only nine trials and that data collection occurred *after* the session involving belief manipulation. Consequently, the lack of results observed should be interpreted with caution.

Table 3.3 Discrimination and self-recognition scores. Overall SDA, IMI & SDIMI values averaged across all factors.

	Discrimination Task	DV measures averaged across all 'self' agent trials (ms)			Identification Task	Tally of 'self' identity responses across stimuli types		
Participant ID (N=12)	% Correct responses (max = 27/27)	SDA	IMI	SDIMI	% Correct responses (max = 9/9)	Agent Self	Agent-other (Paired)	Agent-other (New)
AC	96.3	57.2	39.4	62.5	55.6	3	1	2
AK	96.3	43.6	34.0	47.1	66.7	3	3	0
CL	48.2	69.8	100.9	93.3	66.7	3	2	1
MA	70.4	70.1	89.9	91.2	33.3	0	3	0
SP	66.7	57.1	80.9	66.5	33.3	1	3	1
XS	77.8	33.4	30.1	41.4	11.1	0	3	2
LU	59.3	61.5	101.8	78.4	11.1	0	2	3
CA	81.5	43.8	61.7	55.0	88.9	3	0	1
VE	81.5	59.4	53.6	75.8	55.6	2	2	1
LE	100.0	49.9	78.2	67.0	66.7	3	0	3
FL	63.0	66.5	84.8	77.6	0.0	0	3	3
JA	59.3	100.4	136.9	112.1	66.7	3	2	1
Average scores:	**75.0**	**59.4**	**74.4**	**72.3**	**46.3**	**1.75**	**2.0**	**1.5**

Figure 3.26 Correlation between percentage correct in the discrimination task and the SDA during agent-self trials.

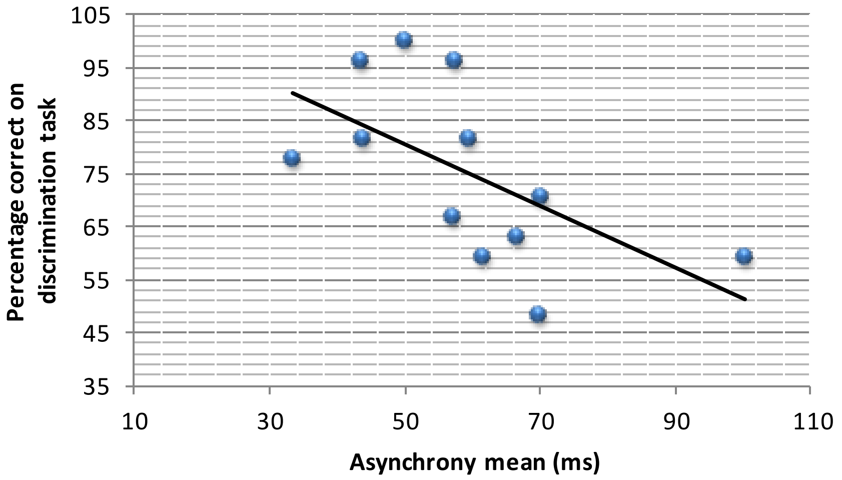


Figure 3.27 Correlation between percentage correct in the discrimination task and the IMI discrepancy during agent-self trials.

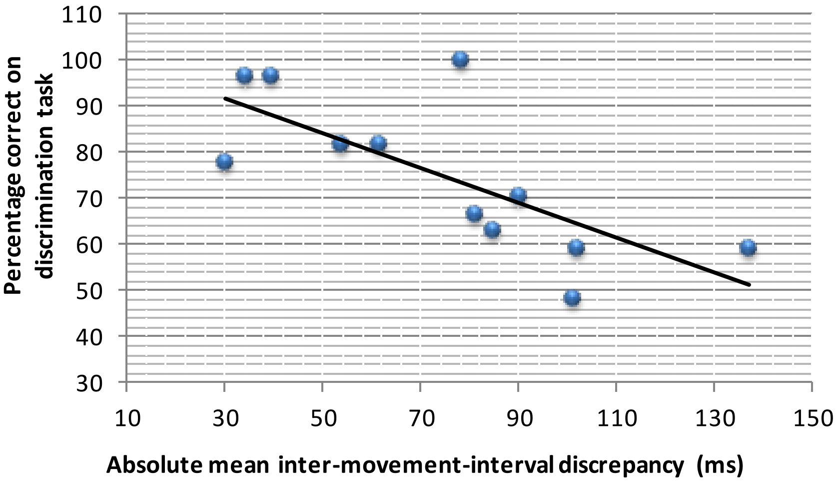
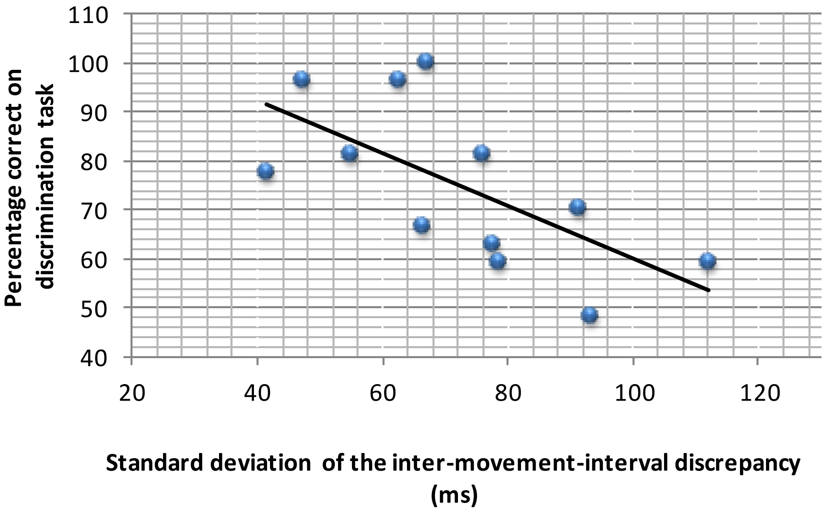


Figure 3.28 Correlation between percentage correct in the discrimination task and the SDIMI during agent-self trials.



3.4.2.2 Peak velocity discrepancies in the stimuli of paired participants

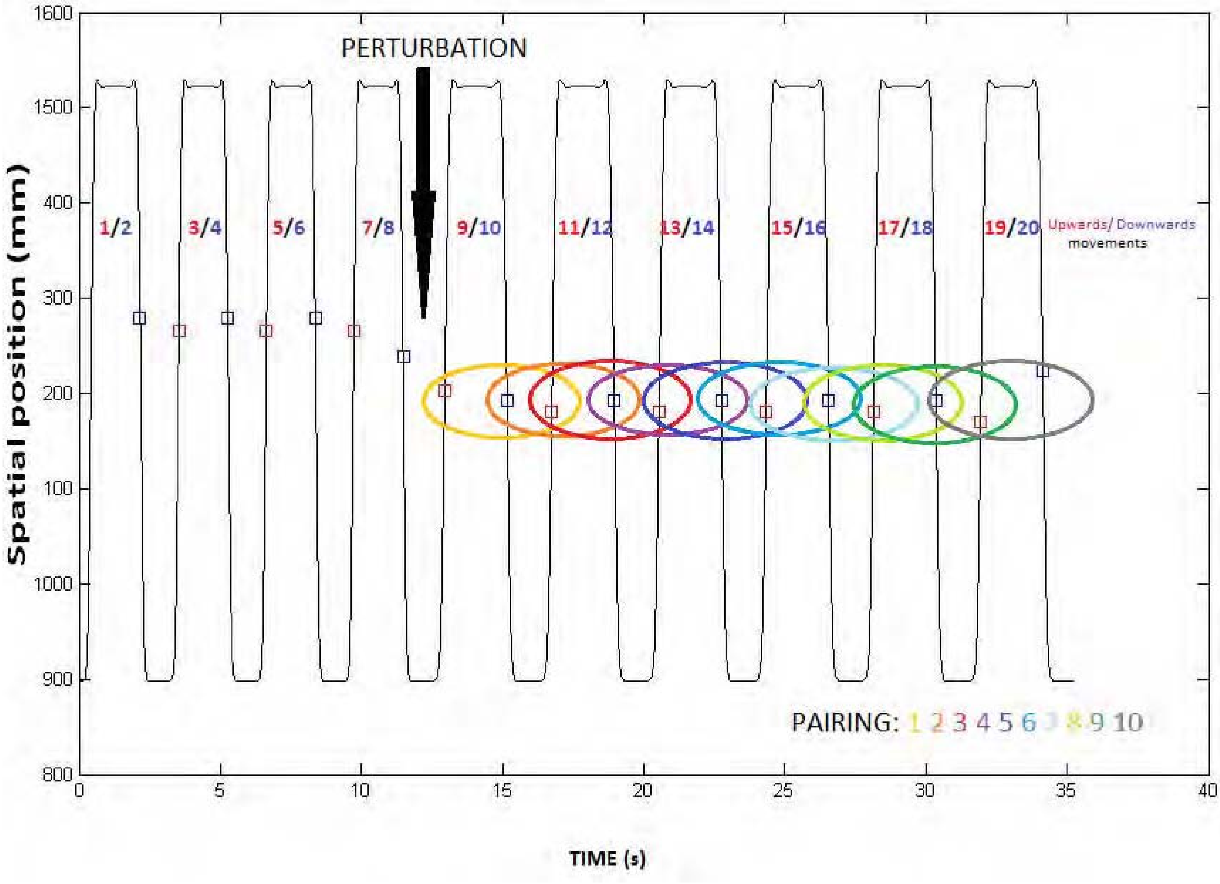
The discrepancies between the peak velocity value in the unperturbed 1000 ms stimulus generated from each participant (agent-self) and the unperturbed 1000 ms stimulus to which they were paired (agent-other) was also correlated against each participant's overall performance (averaged across all factors) on each separate DV, to test whether these discrepancies could account for significant (biased) performance differences. This revealed no significant correlation between discrepancies and performance ($p > .05$). Therefore, differences in peak velocities between agent-self stimuli and agent-other stimuli did not appear to be distinct enough to impact severely on overall measures of performance.

3.4.2.3 Post perturbation recovery

To investigate how well participants recovered following a tempo perturbation, criteria was set to establish the number of movements post-perturbation needed until performance recovered.

As an indicator of recovery, movements following a perturbation were grouped to investigate which three successive movements gave rise to the lowest mean asynchronies (MAs) (Figure 3.29). For brevity, only trials in which perturbation onset occurred after the 4th downward movement (i.e., starting from movement 9 onwards) were examined. This left 10 possible post-perturbation recovery positions ranging from movement number 9 (upwards) through to movement number 18 (downwards). MAs were averaged across the three movements in each of the ten post-perturbation pairings and the pairing with lowest mean asynchrony overall was chosen as the recovery position. Hence if pairing 10 gave rise to the lowest asynchrony, position 18 would be selected. Additionally, the asynchrony value of the least asynchronous pairing was itself recorded. For Session 2, the selected recovery positions and the asynchrony values associated with them (i.e., the recovery values) were then analyzed separately in a 2 (trial type: perturbed F2S or S2F) × 2 (agency: self or other) ANOVA. For Session 3, the addition factor of belief (self or other) was also included in the analysis.

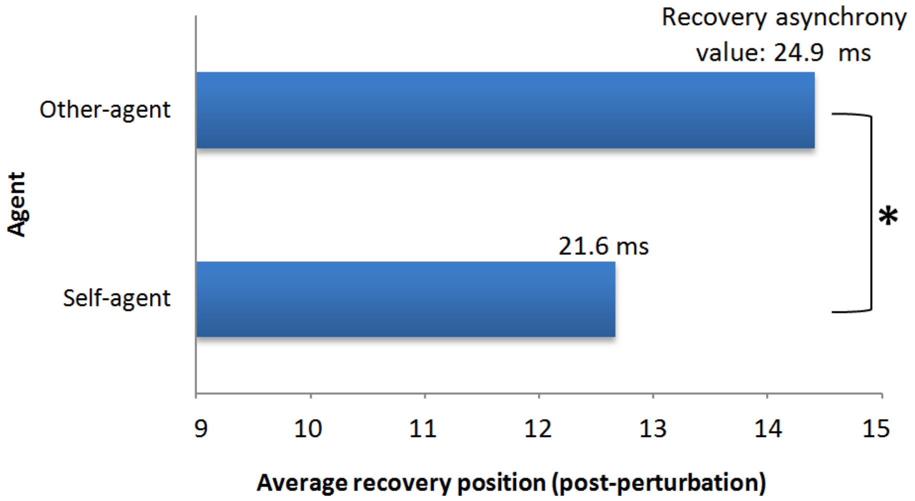
Figure 3.29 Movement pairings which were averaged to establish which three successive movements were least asynchronous.



3.4.2.3.1 Session 2

Only the main effect of agency on selected recovery position was significant, $F(1,11) = 11.31$, $p < .01$, $\eta_p^2 = .51$ (Figure 3.30). This indicated participants recovered earlier in agent-self (average position: 12.67, rounded to upwards movement 13) compared to agent-other (average position: 14.42, rounded to downwards movement 14) conditions regardless of trial type. For the asynchrony value of the chosen pairing, no significant effects were observed ($p > .05$).

Figure 3.30 Session 2: The main effect of agency on movement recovery position following a perturbation.



3.4.2.3.2 Session 3

Unlike for Session 2, no effects of agency were found on recovery position ($p > .05$) (Figure 3.31). However, agency was found to have an effect on the asynchrony value of the chosen pairing, $F(1,11) = 6.59$, $p < .05$, $\eta_p^2 = .38$ (Figure 3.32). This indicated that participants showed less asynchrony in agent-self (22.8 *ms*) compared to agent-other (32.5 *ms*) conditions.

Figure 3.31 Session 3: No difference for agency on movement recovery following a perturbation.

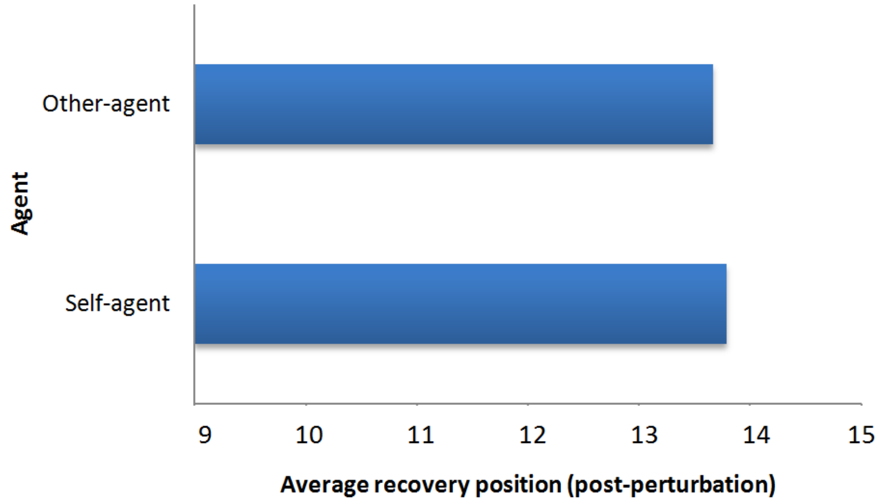
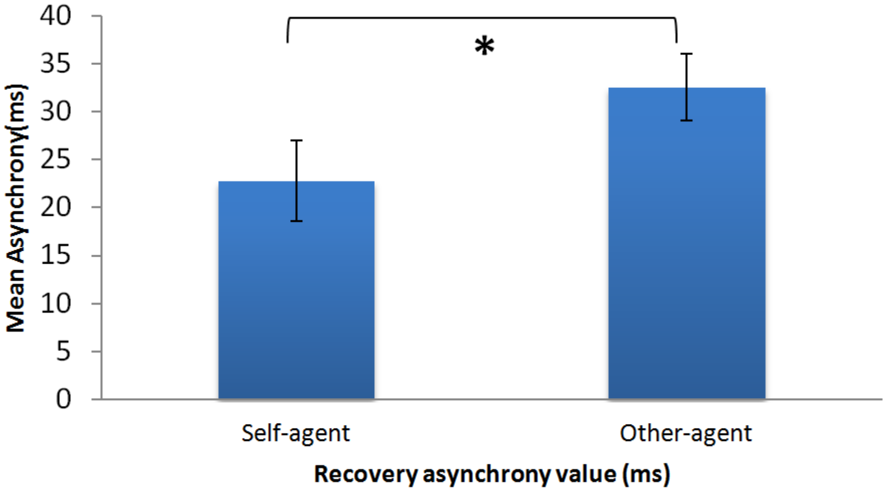


Figure 3.32 Session 3: The main effect of agency on movement recovery values following a perturbation.



See Appendix one for illustrative examples of the MA recovery rates following a tempo change in a perturbed F2S and perturbed S2F trial, respectively. Table 3.4 shows the average values across all factors and all DVs.

Table 3.4 Average values across all factors and all DVs

Session 2							
Factor	Trial Type			Agency		Movement Direction	
Level	Perturbed F2S	Perturbed S2F	Unperturbed	Self	Other	Up	Down
DV	Mean values of each DV for each Factor (ms)						
MA	28.7	33.5	6.3	30.3	15.4	59.0	-13.3
AA	90.0	83.5	82.9	84.1	86.9	90.9	80.0
SDA	59.1	56.6	59.1	58.0	58.5	50.6	65.9
IMI	93.3	75.8	81.1	77.6	89.2	78.5	88.3
SDIMI	93.3	75.8	72.4	73.4	87.7	77.3	83.8

Session 3									
Factor	Trial Type			Agency		Belief		Movement Direction	
Level	Perturbed F2S	Perturbed S2F	Unperturbed	Self	Other	Self	Other	Up	Down
DV	Mean values of each DV for each Factor (ms)								
MA	-4.0	-4.90	-7.3	-3.2	-7.6	-2.6	-8.2	26.5	-37.3
AA	82.6	75.5	77.6	82.2	74.9	76.1	81.0	74.9	82.2
SDA	62.3	56.9	62.3	61.4	59.6	57.2	63.8	66.0	55.0
IMI	85.0	81.4	83.3	77.8	88.7	77.8	88.7	78.8	87.7
SDIMI	72.8	69.5	74.9	72.9	71.8	67.2	77.6	73.7	71.1

3.5 Discussion

This chapter investigated firstly whether synchronization performance was influenced by bottom-up information when the identity (self, other) of the agent whose movements were modelled was unknown, and secondly, whether having a top-down belief surrounding agent identity (whether accurate or not) could also modulate performance.

Findings were predominantly supportive of the hypotheses. Specifically, top-down information about the agency of observed actions was found to influence synchronization performance. Agency-related effects, however, were not unambiguous, as demonstrated by the different larger mean asynchronies for agent-self versus agent-other trials when belief was uninduced (Session 2). Nonetheless, agency appeared to be a predictor of recovery speed following a tempo disturbance, which implied that a self-advantage exists for correcting movements following an abrupt change in tempo. This is perhaps indicative of a reliance on self-generated motor representations when faced with unpredictable situations.

Absolute asynchronies, which spoke to the overall quality of performance in terms of the discrepancy magnitude between participant and display, indicated little in the way of differences across all factors. Nevertheless, mean asynchronies were larger for perturbed trials relative to unperturbed trials. This was not particularly surprising, as during perturbed trials participants had to make an online adjustment of their tempo. Interestingly, the effect of agency revealed that participants' performances trailed less behind the stimulus when the agent in the display was another person compared to when it was themselves. It could be that because stimuli were modified temporally, participants were (implicitly) unwilling to attribute temporally distorted stimuli to themselves (as this did not tally with their experience of performing during the initial recording session). Thus, participants might have treated all stimuli as though generated by another agent. Indeed, it has been shown that the self-recognition advantage is eliminated when temporal features of one's own performance are altered (Cook et al., 2011; Flach et al., 2004).

This account, however, still leaves the curious problem of why in this case, they would be further behind the stimulus, as opposed to similarly behind, for agent-self compared to the agent-other conditions. Moreover, this effect appeared particularly prominent during downwards movements of unperturbed trials, where performance during agent-other trials actually preceded the stimulus. It is possible that the less attention-demanding unperturbed trials gave participants greater opportunity to fully exploit a simulated representation of observed actions. This might have led participants to adopt a more proactive strategy pre-empting the stimulus when bottom-up information (e.g., biomechanical, kinematic cues) indicated stimuli were more difficult/dissimilar to one's own movements, which would be the case during agent-other trials.

Although the asynchronies and IMI failed to provide clear-cut evidence in support of an agent-self advantage in performance, perhaps due to the temporal distortions, data from the period recovery analysis revealed that following a tempo perturbation, participants recovered faster for agent-self trials versus agent-other trials in Session 2. In Session 3, the asynchrony value obtained from the least asynchronous pairing of three successive movements post-perturbation was revealed to be smaller during agent-self trials versus agent-other trials. Therefore, participants appeared to show improved recovery when synchronizing to themselves versus another person, perhaps because they could re-adapt to simulating movements faster and more accurately when observed and executed performance more closely matched.

The IMIs tested the difference in the phase durations of the stimulus's and participant's movements. In Session 2, IMIs and the variability of IMIs (SDIMI) demonstrated that participants were able to match their performance duration with stimuli duration much more accurately and less variably during trials which involved a change to a faster tempo (i.e., S2F) than compared to trials which involved a change to a slower tempo (i.e., F2S). This effect was particularly noticeable during agent-self trials in Session 2. In tapping tasks and expressive piano performance, the variability of intertap intervals (ITIs) (which is proposed to be equivalent to the phase duration of each movement in this current task) is known to increase as ITI duration increases (Peters, 1989; Repp, 1997) and this is thought to reflect timekeeper variance (Wing & Kristofferson, 1973). This effect has been interpreted as an attention-based switch from a more automatic mode of performance during short intervals to a more controlled performance mode for longer interval durations (Peters, 1989). Accordingly, it is not too surprising that the slowing down of tempo later on in F2S trials gave rise to greater discrepancies between observed and executed movements, as slower movements led to increased phase durations. Due to averaging across all movements, the effect was possibly less pronounced when slower tempos were at the beginning of a trial (i.e., perturbed S2F trials) as these could have been masked by the initial adjustment epoch at the onset of all trials needed so as to enter the rhythm of that trial.

The differences observed between upwards versus downwards movements are similarly intriguing. Upwards executed movements typically trailed behind stimuli (reactive behaviour), whilst downwards movements tended to precede the stimuli (anticipatory behaviour). It is worth remembering that upwards movements, unlike downwards movements, were motorically (e.g., biomechanically) accurate. Downwards movements were, in fact, a reversal of an upward movement and hence did not veridically reflect the kinematics of a downwards-executed movement (i.e. they were not motor-true portrayals of executed action). By virtue of this, different performance tactics may have been employed for upwards versus downwards movements. This is corroborated with the evidence suggesting upwards movements were more controlled, as they required participants to decide on an endpoint. In contrast, downwards movements ended upon hand contact with the hip, which provided a definitive endpoint and meant less need for active deceleration (which would likely increase asynchrony). Instead, participants could effectively 'collapse' into the downwards rest position. This is substantiated with the negative asynchronies for downwards movements indicating participants were anticipating these movements more. The variability of the asynchronies (SDA) and the measures of discrepancies in phase duration (IMI, SDIMI) also indicated that participants were less variable for upwards movements, irrespective of all other factors, which supports the notion that these movements were far more carefully controlled.

Of particular interest, the variability of asynchronies (SDA), which is seen as a key indicator of synchronization skill (Repp, 2005), unveiled an effect of belief. This showed that participants were less variable at keeping in synchrony with the stimulus when they believed they were synchronizing with themselves versus another person, irrespective of who they were actually synchronizing with. This provides direct support for the primary hypothesis that belief would have a top-down influence on synchronization performance. The result is especially striking, given that trials were not blocked, but were instead fully randomized.

Furthermore, IMIs for Session 3 also showed that the ability to match stimulus duration was better when participants believed they were synchronizing with themselves rather than another person. Moreover, this belief effect appeared to be specifically pronounced when the agent in the stimuli was another person. When compared against the data for agent-other trials, when belief was uninduced (Session 2), the results hint that a top-down belief effect may be specifically operating to modulate performance when the stimulus is labelled as 'other' and is indeed derived from someone else. In terms of attention and gating theories, it could be that there are sequential (or possibly 'weighted' parallel) stages involved in the processing of observed biological motion that might help explain this result.

The direct matching system proposes that observed and executed actions are co-represented within the same motor system (see Rizzolatti, Fogassi, & Gallese, 2001). Some have argued this direct matching system is tuned towards representing the actions of biological agents (Kilner et al., 2003), although more recent evidence suggests that matching is not entirely immune to the influence of non-biological motion, especially when motion is construed as intentional (Liepelt, von Cramon, & Brass, 2008; Stanley et al., 2007). Thus it seems that an initial stage in motion processing might assess movements for biological plausibility. Gating theory (Liepelt & Brass, 2010) would suggest that as all of the stimuli used here were biologically derived, access to the mirroring system, where direct matching takes place, would be granted. Similarly, informing participants they were watching human motion profiles (self, other) would have brought biological plausibility into focal attention, possibly encouraging simulation (Longo & Bertenthal, 2009).

Thus the primary representation strategy is heavily reliant on bottom-up sources of information, which are used to drive an internal simulation of the observed action based on personal experience. However, by virtue of the fact that observed and executed mappings more closely match (i.e., strong resonance) during agent-self trials, these trials will be performed with little interference to ongoing motor output, regardless of 'self' or 'other' belief labelling. In contrast, observing agent-other stimuli would lead to greater conflict between observed-executed mappings (i.e., weak resonance), a result which might prompt the system to take in additional top-down information to aid performance (second stage processing). A 'self' label under weak resonance conditions might, for instance, direct more attention to the more 'difficult' stimulus, enabling more careful performance. An 'other' label, on the other hand, could suggest the futility of attempting to further simulate performance using one's own highly personally-tailored motor representation. If the case, motor resonance with one's own motor repertoire could to be attenuated in favour of a more general representation (e.g., more relaxed parameters governing biomechanical degrees of freedom, more reliance on spatial cues etc.), perhaps equivalent to representations active during interactions with agents explicitly informed to be non-biological. This could in effect be seen as a 'kill switch' mechanism in the gating system which allows representations granted access to the system to be re-evaluated and re-routed when they fail to accurately predict the observed actions. Thus here for example, having an 'other' belief would throw the 'kill switch' earlier allowing alternative representations less prone to motor-interference to be employed.

Aiding this decision to reassess representation choice could be the 'social interaction loop' in which the state of others in response to one's own motor command is estimated (see HMOSAIC in Wolpert, Doya, & Kawato, 2003). Here, the predicted response generated by internal models (Miall & Wolpert, 1996) is contrasted against the response reality (via sensorimotor feedback) and discrepancies between observed and predicted actions are used to update subsequent motor commands. It could be suggested that weaker resonance (i.e., the discrepancy term) during agent-other compared to agent-self trials might lead to revision of the representation used to model performance, especially when continuing to use one's own tailored representation is seen as probably futile.

It is also possible that attention was simply biased away from motion labelled as 'other', which could reduce performance in such conditions. However, this seems unlikely, given that humans are socially motivated beings and attending to others is not only advantageous but necessary towards effective interpersonal actions. In fact, people might even try harder to cooperate when engaged with others due to social affiliation and equity concerns (Lakin & Chartrand, 2003; Sanfey, 2007). One might surmise that had the nature of the current task been more social, involving synchronization with a real-life agent, a tendency to remain more focused might have prevailed under agent-other conditions. In fact, when agency was unknown (Session 2), participants were more pre-emptive of the stimulus on agent-other trials rather than agent-self trials.

It could be proposed that top-down information during sensorimotor synchronization is potentially only taken in subsequent to an attempt to simulate movement based on one's own motor repertoire. Consequently, belief surrounding agency may not be able to entirely override bottom-up (agency) effects. So long as the simulation provides a good degree of match between observed and executed performance, there remains no need to access top-down assistance. Once a substantial discrepancy arises, however, performance could be re-evaluated and a (top-down-modulated) weighted decision made as to either continue with the same representation criteria or to pursue an alternative approach (e.g., change parameters of the representation). Further evidence for a top-down effect of belief also came from SDIMIs in Session 3. Here the stimulus–participant duration discrepancy was less variable for both upwards and downwards movements when participants believed they were synchronizing with themselves compared to another person.

Given the evidence from Keller et al. (2007), this chapter also tested whether participants who were better at synchronization were also better at self-recognition. No such effects were found, however. Caution is advocated in interpreting this lack of effect for two reasons. Firstly, the correlations were based on data from only nine trials and, secondly, data collection occurred after the session involving belief manipulation. This meant that belief effects might have confounded responses decisions, as participants might have considered the task a 'memory' task to identify stimuli given the 'self-label'. This is supported by the numbers of 'self' responses reported for agent-other stimuli. Consequently, the lack of support for a self-recognition advantage here does not contradict previous research findings, which chiefly indicate that a robust self-recognition phenomenon exists when beliefs are unaltered (Beardsworth & Buckner, 1981; Cutting & Kozlowski, 1977; Flach et al., 2004; Keller et al., 2007; Knoblich & Prinz, 2001). Further support for this comes from the fact that when participants were asked to simply discriminate between stimuli in general, without being questioned on identity, those who were better at the discrimination task also tended to show less variable performances in both asynchronies and phase duration discrepancies.

There were some limitations in this current study worth mentioning. Firstly, it is critical to acknowledge that it is not possible to confirm with certainly whether the belief manipulation actually functioned in the manner in which it was anticipated, if at all. It is impossible to know what participants actually believed on any given trial, especially given the intermingled dispersing of belief conditions over the course of trials. Indeed an analysis of the time course against performance might be a fruitful course to pursue in future work, especially if belief about preceding trials had the ability to impact on later ones. Anecdotally however, participants largely reported that they had no suspicions regarding why they were being told who they were synchronizing with. Hence the strong self-belief advantage remains curious and the manipulation was possibly not wholly confounded.

Another point to raise is the relevance of self-synchronization for study, given that a person rarely (with the exception of for instance within-person bimanual limb coordination) needs to synchronize with an external representation of their own performance, whereas between-person synchronization with others is a common experience. Clearly sportspeople might watch videos of their performance to aid training and dancers might practice in front of a mirror, but they do not usually 'synchronize' to these displays. Thus the prevalence here for superior self-belief performance remains interesting. The implications of a self-belief advantage might have particular practical relevance to motor rehabilitation or indeed in the development of training techniques for use in SMS-based performance such as dancing or synchronized swimming. It underscores the suggestion that it might be advantageous for patients undergoing physiotherapy for an operated limb to practice regularly with movement recordings of their healthy limb, for example.

To conclude, the data here strongly suggest that top-down information, in the form of belief surrounding the agency of observed actions, can impact on synchronization performance. Familiarity or at least convinced familiarity with the agent in the display may influence performance by determining the degree to which participants exploit the motor resonance mechanism in their own motor system. Correspondingly, beliefs about agency may be acting on attention-based mechanisms, allowing one's synchronization efforts to be channelled or focused more carefully towards processing some cues over others, in circumstances where top-down information deems such cues as worthwhile or not.

Whilst this current work has provided further evidence to support both attention and gating theories, it is limited in not being able to differentiate between these two hypotheses. It may be the case that both theories play a role. However, establishing the relative contribution from these theories should be seen as the next step in investigating top-down modulation of motor behaviour. One way to do this in future would be to implement a two-tier reward system for performance. For example, participants could be rewarded according to their overall performance in both belief conditions; however, a bonus reward could be allocated for particularly good performance in the other-belief condition. Thus attention should be especially focused on performing well in the other-belief condition (partially eliminating the argument that attention is simply more focused during self-belief conditions because these conditions are more salient). Meanwhile, performance in the self-belief condition should not be compromised because it remains important to do well overall.

If attention was a more important determinant of synchronization performance than motor congruence, then it might be expected that participants would show the reverse pattern of results, namely, improved synchronization in the other-belief condition. Alternatively, if believing one is synchronizing with oneself gives rise to superior performance despite there being a reward to perform better in the other-belief condition, this would weaken the attentional argument. It would, however, still not eliminate the attentional argument completely, as it might be that it is simply 'easier' to always attend to stimuli thought to be one's own. This exposes one difficulty with the attentional argument, as it is impossible to eradicate the influence of attention and instead it is only possibly to bias attention in a particular direction and study its effects in that way.

Future work should also investigate the neural correlates of belief, with particular consideration being paid to the paracingulate cortex as a possible gatekeeper mechanism. This area shows greater activation for stimuli interpreted as human in origin, regardless of whether the stimuli is in fact of a biologically low realism (Stanley et al., 2010). One might anticipate activity in this area to also increase as a function of whether the actions are construed as self-generated or not. For instance, greater activation might be predicted in this region for self-belief versus other-belief conditions. Particularly interesting would be any differences in activation arising from a mismatch between true agency and agency-belief information, which might be diagnostic of a 'kill switch' decision area in the gating mechanism.

In summary, both bottom-up and top-down information appear to have the ability to improve or impinge on synchronization performance. The study of bottom-up influences on motor performance has yielded interesting findings that bolster the notion of a direct matching system of observed and executed actions (Brass et al., 2000; Kilner et al., 2003). By comparison, top-down modulation of motor behaviour is largely under-explored, possibly due to the associated cognitivist connotations which are difficult to capture empirically. Further research in the field of interpersonal action is essential, and specifically with active rather than passive performance paradigms involving live agents agent as opposed to stimuli recordings. Novel brain imaging techniques such as dual scanning (Blakemore, Winston, & Frith, 2004) which allows interacting individuals to be scanned simultaneously, could be one invaluable source of contribution to this goal. Unfortunately, however, motion artefacts impose severe constraints on the types of motor behaviour that can be studied in such environments. Furthermore scanner environments do not embody real life situations and for these reasons behavioural work should remain imperative. This present study has provided an initial step beyond the study of motor response differences between biological and non-biological agents, to investigate how beliefs about human agents influence motor behaviour in an active synchronization paradigm.

CHAPTER FOUR

FITTS' LAW: DOES IT HOLD FOR INTERPERSONAL ACTIONS?

4.1 Introduction

Fitts' Law neatly captures the speed–accuracy trade-off that typifies human motor behaviour. In simple terms it states that movement time toward a target increases as the target width (size) decreases and as the target distance (amplitude) increases. This present study investigated whether Fitts' Law also holds true during an interpersonal task which demanded that the participant place down a target in order for their task partner to hit it. The hypothesis tested was that under speed pressure, participants would place smaller targets closer to their interaction partner in a bid to implicitly reduce the index of difficulty their partner would experience in hitting the target. Presumably such a process might involve representing the task of the other player in addition to one's own task.

The information capacity of the human motor system was investigated by Paul Fitts (Fitts, 1954) through a series of cleverly designed experiments in which he varied movement amplitude and tolerance parameters by manipulating both the distance between targets and the size of those targets. In one task, participants repeatedly tapped two metal target plates in alternation using a stylus. By manipulating the distance between the target plates as well as their width, conditions with varying levels of difficulty were created. Performance rate was measured whilst participants performed as quickly and as accurately as possible, although accuracy was emphasized above speed.

By holding constant movement amplitude and tolerance factors, it was possible to construct experimental conditions in which it became feasible to deduce that performance rate was constrained principally by the capacity of the motor system (Fitts, 1954). Through the framework of information capacity theory as adapted from Shannon's Theorem 17 (Shannon & Weaver, 1949), Fitts was able to reconcile in a quantitative manner the relationship between the amplitude, duration and accuracy of movement responses. Fitts demonstrated that increasing the speed of successive movements of fixed amplitude could lead to reduced accuracy, as less information was available per movement. Moreover, increasing the amplitude of movements also reduced accuracy and/or increased response duration. Crucially, Fitts deduced that the changes in response duration and accuracy which manifested as a modulation in response variability should be changed in a measurable and interrelated way.

In each of his experiments, as the movement amplitude was reduced and as tolerance was relaxed, the performance rate improved. To quantify these observations, Fitts formulated an index of difficulty (ID) measure specifying the average minimum amount of information necessary to control a motor response in a task of fixed amplitude and tolerance limits. He defined the index of difficulty by the following equation:

$$\mathrm{ID} = \log_2(2\mathrm{A}/\mathrm{W}).$$

Here A refers to the amplitude of movement whilst W represents the width of the target or 'tolerance range'. Fitts was able to use ID to predict movement time (MT) based on the equation:

$$\mathrm{MT} = \mathrm{a} + \mathrm{b}\cdot\mathrm{ID},$$

where a and b represent empirical constants. It is worth noting another commonly used formulation known as the Shannon formulation in which ID is computed based on the *unaltered* Shannon Theorem 17, where ID = $\log_2(1+A/W)$ (MacKenzie, 1989). MacKenzie (1989) has shown that the use of this formulation actually provides a closer match to the data and it also has the advantage of not allowing the ID to be negative, which is useful when modelling performance.

These simple yet compelling equations underpin what is now referred to as Fitts' Law, a law which quite simply states that the time taken to move between two targets as rapidly as possible is dependent on the distance by which they are separated as well as their width. The shorter the distance between the two targets and the larger the target widths are, the better the performance. Although these findings might appear modest and perhaps even obvious, Fitts' Law is deceptively powerful and its repercussions have real practical application for many areas of life (e.g., ergonomic design).

The robustness of Fitts' findings were further reconfirmed more recently when Decety and Jeannerod (1995) were able to show that Fitts' Law also held true for motor imagery. Participants were asked to imagine walking down a path and through a gate. As predicted by Fitts' Law, the average imagined walking durations in all participants increased as the gate distance increased and as the gate width decreased. These findings provided valuable evidence that the constraints of the motor system are also reflected in motor imagery.

With Fitts' Law holding true for action production (Fitts, 1954) and motor imagery (Decety & Jeannerod, 1995), Grosjean, Shiffrar and Knoblich (2007) went one step further to test whether Fitts' Law would also remain valid for the perception of other's actions. This would make Fitts' Law perhaps the first motor phenomenon to be studied in all three domains (Grosjean et al., 2007). In Grosjean et al.'s task, participants viewed an apparent motion display of two alternating paired images in which a human model appeared to 'move' their index finger between a left target line (image 1) and a right target line (image 2). Participants had to decide whether they thought it was possible or impossible for the model to move between targets at the speed displayed on a particular trial without missing the targets.

Perceived MT was defined as the speed at which participants were equally likely to indicate a stimulus frequency as possible or impossible to perform. A linear analysis on these perceived MTs with ID as the predictor variable revealed a highly significant positive relationship. This result implied that perception of action is influenced by the constraints of the motor system in much the same way as actual motor production is.

Whilst most of the evidence seen so far supports the capacity of Fitts' Law to accurately model some key aspects of human motor behaviour, a number of exceptions to the law have been reported (Adam, Mol, Pratt, & Fischer, 2006; Chi & Lin, 1997). Adam et al., (2006) reported a violation of Fitts' Law for rapid discrete pointing movements made in a structured array, compared to movements made towards a single isolated target in an otherwise empty workspace. Fitts' Law would predict linear increases in MT for further distances, irrespective of the presence of placeholders (which mark all possible target locations). However, MTs to the most distant target were shorter than MT to the second-to-last target when placeholders were present. Thus, whilst Fitts' Law provides an excellent account of performance with traditional single-target displays, it is less proficient at explaining performance with multi-element displays.

Given the generally good agreement between Fitts' Law and movement execution, observation and imagination, the current study addressed whether the fundamental predictions of Fitts' Law could be extended to interpersonal dyad interactions. Until recently there had been only one study examining Fitts' Law in an interpersonal paradigm using reciprocal movements (Mottet, Guiard, Ferrand, & Bootsma, 2001). Very recently however, another paper has been published addressing the same question (Fine & Amazeen, 2011).

Mottet et al. (2001) used a variant of a Fitts task in which participants had to bring as rapidly as possible a pointer operated by one manipulandum in line with a target whose position could also be moved simultaneously with the use of another manipulandum. The authors compared a bimanual within-person two-handed version of the task against a two-person version of the task in which each participant independently operated one of the two manipulanda. Mottet et al. (2001) tested whether the partition of work across both hands would be symmetric or asymmetric. For instance, one hand might be heavily involved in the majority of the movement, producing the initial ballistic aiming movement out towards the target, whilst the other hand might simply apply last minute corrections of the target position needed to bring target and pointer together (i.e., asymmetric condition). Alternatively hand movements could act as coupled oscillators that tend to act in synchrony with similar kinematic trajectories (i.e., symmetric condition) (see Kelso, Southard, & Goodman, 1979). Mottet et al. (2001) hypothesized that regardless of whether the hands belonged to the same individual or not, Fitts' Law should hold.

They found that for both bimanual and interpersonal actions the MT taken to bring the target and pointer in line with each other increased linearly as the targets became spread further apart or as the targets became smaller. Their study provides evidence of the generalizability of the Fitts' Law phenomenon to cases of multiple persons acting together. Furthermore, the underlying kinematic patterns for the two-person task also resembled those seen in the bimanual condition. As the ID increased, not only did the MT increase, but the organization of the movement kinematics also gradually shifted from a harmonic (sinusoidal-like) profile to a decidedly non-linear profile. They argued that this similarity across both conditions demonstrated that Fitts' Law held true in cooperative two-person aiming, which hence suggests that the law is not readily influenced by the numbers of effectors or the numbers of people controlling those effectors. Instead, they hypothesized that Fitts' Law requires a more general abstract descriptive framework (i.e., task space reference) which concerns itself with the relative motion between the objects moving toward each other.

By contrast, Fine and Amazeen (2011) recently reported a violation of Fitts' Law for both intrapersonal and interpersonal performance, in a task involving rhythmical tapping between targets. Previous research had already shown that when participants coordinate such tasks bimanually with mismatching indices of difficulty across both hands, relative to unimanual performance, MTs of the hand experiencing the easier (lower ID) condition became prolonged so as to mimic the MTs of the 'difficult' hand (Kelso et al., 1979). This clearly violates Fitts' Law, which would predict that MTs to the easier target would have resulted in faster MTs for the hand performing in this easier condition.

Extending these findings, Fine and Amazeen carried out a reciprocal aiming task with target pairs which were either easy or hard and this could vary across both hands or both participants. In the bimanual condition, each participant was responsible for tapping between target pairs on both sides of the workspace, whereas in the interpersonal version each participant tapped with one hand to the target pair on their side of the workspace. Participants were permitted to choose their own tapping frequency so long as they performed accurately and quickly. Results showed that when target IDs were unequal across both hands or both participants, MTs of the hand working on the easier target became lengthened and the two oscillating limbs also entrained, violating Fitts' Law in both intrapersonal and interpersonal conditions. This result was taken as strong support for a non-centralized coordination mechanism, as no physical coupling between limbs existed in the interpersonal task and coordination was brought about instead presumably by visual coupling (see also Richardson, Marsh, & Schmidt, 2005; Schmidt, Carello, & Turvey, 1990). However, the direct anatomical coupling between limbs in the bimanual task may still have yielded some benefit to the task, as compared to interpersonal coordination; indeed, bimanual coordination showed better stability as measured by the average standard deviation of relative phase between limbs.

The link between perception and action posited in theories of common coding (i.e., neural simulation) that draw on evidence from the mirror neuron system may provide one potential mechanism for the emergence of such interpersonal coordination, by suggesting that the goal of one's task partner can become co-represented along with one's own goal (Sebanz, Bekkering, & Knoblich, 2006; Sebanz, Knoblich, & Prinz, 2003). Fine and Amazeen (2011) point out, however, that dynamical coupling may pose a constraint on neural simulation approaches, as participants did not directly match movements in a 1:1 manner. Had they done so, amplitudes, in addition to MTs, would have been affected by discrepancies in ID for observed and executed actions in the interpersonal condition.

Therefore, whilst Mottet et al. (2001) provided support for Fitts' Law in an interpersonal reciprocal pointing task, Fine and Amazeen (2011) clearly showed a violation of the principles of the law for between-person interactions. Such conflicting evidence points out the difficulties in studying interpersonal performance which appears to be heavily influenced by the experimental design and variables chosen for investigation.

In the research reported in this chapter, a reciprocal (i.e., here a single reach-and-return movement) version of a two-person aiming paradigm was used. In motor control research there has been considerable amount of work examining the differences in the underlying kinematics of discrete versus reciprocal movements (Adam, van der Bruggen, & Bekkering, 1993; Guiard, 1993, 1997; Mottet & Bootsma, 1999; Sternad, Dean, & Schaal, 2000; van Mourik & Beek, 2004). Reciprocal movements are those in which, for instance, a stylus is moved between two targets repeatedly over, say, 10 movements (see Fitts, 1952). Reciprocal movements have the advantage of being able to exploit properties of the motor system which enable more efficient energy expenditure during limb movement; however, they have the disadvantage of not having well defined start and end points (Bootsma, Fernandez, & Mottet, 2004). Discrete movements, on the other hand, have very well defined start and end points beginning at movement onset and ending where the movement terminates. During reciprocal tasks it has been observed that the kinematics associated with cyclical action appear to be non-linear and change according to some critical value of the ID reported to be roughly ID = 4.4 (Guiard, 1997). For IDs below this value movements remain cyclical. However, at IDs above this value, movements become much less harmonic and show kinematics which are normally associated with discrete actions, hinting at a switch in how reciprocal movements are organized by the motor system so that previously cyclical movements evolve into concatenated discrete movements (Bootsma et al., 2004; Guiard, 1993, 1997; Mottet & Bootsma, 1999). For the purpose of this current experiment, a reciprocal reach-and-return movement was used. This was aimed at re-evaluating the previous findings of Mottet et al. (2001) and Fine and Amazeen (2011) who had also used repetitive reciprocal movement paradigms.

This current study examined whether individuals would act (implicitly) to reduce the index of difficulty for their partner when engaged in a cooperative target-aiming task with the joint aim of performing as quickly and as accurately as possible. Target width was varied across trials to test whether participants would reduce the amplitude of the movement required for their partner to hit the target by placing the target closer to them. Specifically, might participants place smaller targets closer to their interaction partner, as this might make the task easier for their partner? The hypothesis was that there would be a main effect of target size on the distance at which targets were spontaneously placed during interpersonal trials. In addition, baseline trials were run to test whether Fitts' Law held true in within-person performance, with the standard hypothesis that as ID increased so too should MT.

Three experiments were run with slight modifications of either apparatus set-up and/or procedure. Each is described separately. Prior to participation, all volunteers provided written informed consent. All error bars represent ±1 standard error of the mean.

4.2 Experiment I: Original set-up

4.2.1 Method

4.2.1.1 Participants

Sixteen healthy participants (12 female) with a mean age of 25.6 years (SD = 5.3 years) were recruited from the University of Birmingham student community. All participants were right-handed (self-reported) and had normal or corrected-to-normal vision. Participants were compensated with a choice of either research credits or £7.50 cash for their time.

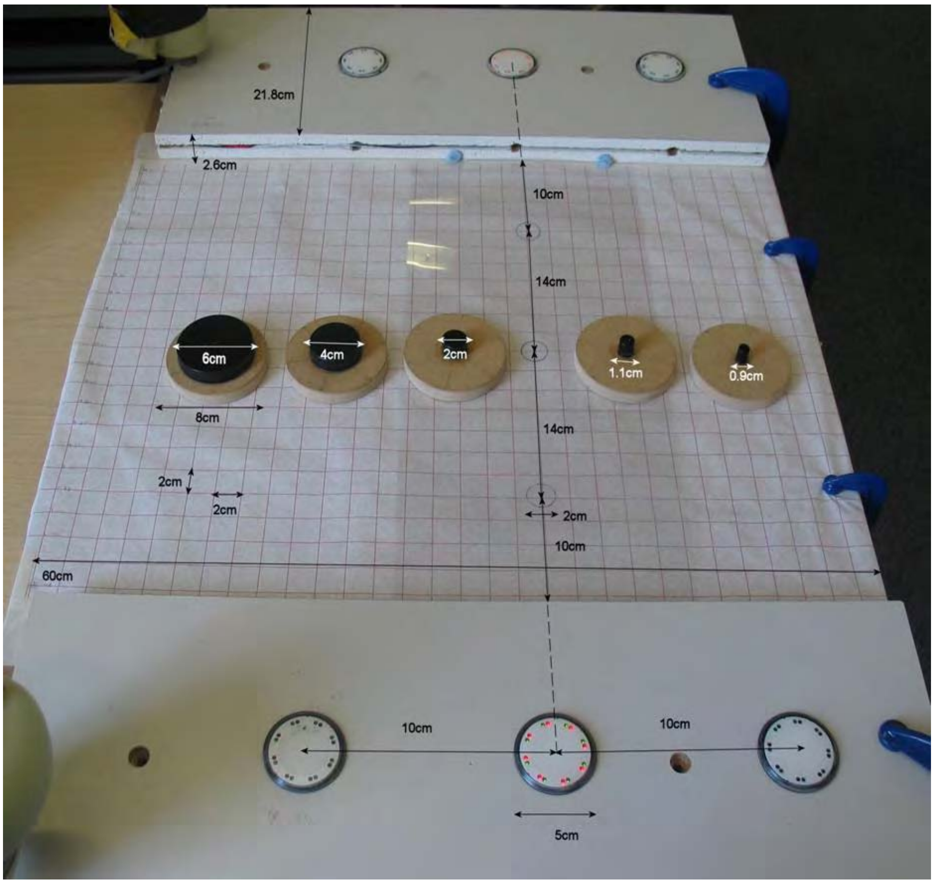
4.2.1.2 Apparatus and Materials

The apparatus consisted of two wooden panels with dimensions 2.6 cm (H) × 21.8 cm (W) × 58.4 cm (L) each embedded with three circular electro-conductive buttons used to record MTs (Figure 4.1). The panels were aligned in parallel lengthways separated by a distance of 64.8 cm as measured from the centre of the middle button on one panel to the centre of the middle button on the panel at the opposite end of the table. Only the middle button on each panel was active for use during recordings and was illuminated using LEDs for this purpose. Each middle button had a diameter of 5 cm and was separated from the other two identical buttons on either side of it by a distance of 10 cm from centre to centre. The buttons were raised approximately 3 mm above the surface of the panel in which they were embedded. Both panels were elevated from the workspace by a height of 2.6 cm and on the table between the two panels a large printed 2 × 2 cm paper grid was laid out covering a workspace area of 48 cm (W) × 60 cm (L).

For the first part of the experiment (Session 1), a transparent sheet of plastic paper measuring 21 (W) × 48 cm (L) was used. On this transparency, the outlines of three marker circles (2 cm diameter) were drawn using permanent marker. This sheet could be fixed into place over the workspace grid using Blue Tack, so that the centre of all the circles drawn on it lined up with the centre of the active buttons. The circles were drawn so that the central circle was equidistant from either panel edge at a distance of 24 cm. The other two circles were drawn either side of the middle circle so that they were 14 cm away from the central circle and 10 away from the panel edge closest to them.

The stimuli used in the experiment were five different-sized wooden targets, each consisting of an identical circular base (8 cm diameter) centrally fixed with a raised circular target which varied in size and was painted in black. The possible target size diameters were 0.9 cm (Target 1, 41.3 g), 1.1 cm (Target 2, 42.2g), 2.0 cm (Target 3, 43.4g), 4.0 cm (Target 4, 51.0g) and 6.0 cm (Target 5, 64.0g) (Figure 4.1). The combined height of base and target was 2 cm. Finally, a custom built Matlab (Mathworks, MA) script was used to produce auditory go signals and to record MTs from the buttons.

Figure 4.1 Experiment I: Set-up and targets.



4.2.1.3 Design and Procedure

The experiment was a within-participants repeated-measures design spread across two sessions held on separate days. Participants were tested individually in Session 1 and with another participant in Session 2. Participants first read through instructions and following this they were sat in a chair as close as was comfortable to the button panel in front of them.

4.2.1.3.1 Session 1

This session served as a baseline measure of each participant's individual performance in the task. The transparency was fixed into place so that participants could see the three marker circles on the grid in front of them. Each marker was set at a fixed distance (Distance 1: 20.2 cm; Distance 2: 34.2 cm; Distance 3: 48.2 cm) as measured from the centre of the starting button. Only one button on one panel was active for this baseline task. Prior to each trial the experimenter placed one of the five possible targets on to the unused button located to the right of the middle button. Targets were selected in pseudo-randomized order of size.

To begin a trial, the participant rested the index finger of their right hand on the active illuminated button. On the go signal, the participant picked up the target placed to the right of them and placed it down so that it fully covered one of the three markers on the workspace in front of them. As soon as this was done the participant was required to move their index finger back to the active button in order to end the trial. Another brief tone sounded on contact with the button and MT was recorded. Altogether this was known as a 'placement trial' (Figure 4.2a). Importantly, participants always picked up targets not by the black target itself, but instead by grasping the wooden base which was the same size across all target conditions. Participants knew in advance which marker they would be covering. Marker location was blocked so that the first third of trials (25 trials) were performed on one marker before moving on to the next marker and so on. These blocks were randomized across participants.

Following each placement trial, the participant performed a 'pointing trial' in which they touched the black target on the disk that they had just placed down in front of them. Participants began the trial with their right index finger on the active button. Upon hearing the cue signal, participants released the button, rapidly reached out to and touched the black target with the tip of their index finger, before once again returning their finger to the active button which registered their MT (Figure 4.2b). After each paired placing and pointing trial had terminated, the experimenter removed the target from the workspace and prepared a new target for the next placement trial. Participants were instructed to always perform their movements as quickly and as accurately as possible. There were five repetitions of each of the five target sizes at each of the three marker locations so that in total each participant performed 75 placement trials and 75 corresponding pointing trials. At the end of this session, a measurement of arm length was taken in order to match each participant up to an appropriate partner in Session 2.

4.2.1.3.2 Session 2

Participants returned in pairs for the final session 1–14 days after Session 1. In total 8 participant pairs were tested, formed by pairing two same-sex participants roughly matched for arm length. In the worst matched case, there was a discrepancy of approximately 6.5 cm in arm length between participants, whereas in the best cases this difference was only about 0.5 cm (μ = 2.67 cm). Participants were informed that although similar in nature to the previous task, the task in this session would crucially now be performed in conjunction with their task partner under the instruction: "Your mutual aim is simply to perform the task as QUICKLY and as ACCURATELY as possible". On half of the trials participants were responsible for placing the target down whilst their partner was in charge of hitting it, and for the remaining half of trials these roles were reversed. Participants were instructed not to communicate with each other during testing. Following instructions, participants were seated opposite one another at the table and directly in front of their own button panel whose central button was active. Between the two panels lay the grid workspace now free of markers. The experimenter informed the participants of which roles ('target placer' or 'target pointer') they would adopt for the first 50 trials.

Prior to each trial the experimenter placed down one of the five targets in pseudo-randomized order of size on to the unused button right of the active button on the target placer's panel. Both participants commenced with their right index fingers on their button.

After the go signal, the target placer released the button, grasped the target by its base and placed it somewhere in the workspace before returning their finger back to its origin. The length of time taken for the placer to perform their part of the task was thus recorded. If asked beforehand where best to place targets, the experimenter simply stated that targets should be placed wherever the participant felt would be most efficient in terms of the overall speed and accuracy of the trial as a whole, as emphasized in the instructions. Similarly to the placer, the target pointer's MT was recorded beginning from the point at which they released their button to the point at which their finger had returned to the same button, after completion of the target aiming. As previously, they had to ensure that they touched the black target with the tip of their index finger. In Experiment I, target pointers could begin their movement anytime after the target placer had begun. Thus, pointers were not required to wait for placers to have returned to their starting position before initializing their own movement. They were told if they explicitly asked, that it was up to them to choose to wait or not, so long as they completed the task in the manner they felt would be most efficient as per instructions. A trial hence started at the onset of the placer's movement and finished with the offset of the pointer's movement (Figure 4.3).

After each trial, the experimenter took a manual measurement of the distance at which the target had been placed from the centre of the target placer's button to the centre of the target. Lateral displacement was not measured. Each participant performed 100 trials. In 50 they acted as target placer and in 50 they acted as target pointer. Participants remained in the same seat for both roles.

In both sessions placement trials were repeated if participants failed to completely cover the marker (baseline trials) or if they accidentally dropped or mishandled the target. Likewise, pointing trials were discarded and repeated if the participant failed to come into physical contact with the black part of the target as instructed. In addition to the primary go-signal, a brief softer tone was used to indicate both when a button had been released as well as when it had pressed. These tones were principally to aid the experimenter in being sure that all movements were correctly recorded. At the end of the experiment, participants were debriefed and asked to indicate if they had ever met their task partner before, as cooperation might have been heightened between friends. Only one participant across all pairs reported having seen their partner before, but they indicated that they had never actually spoken to them.

Figure 4.2 Example of a baseline placing (a) and pointing (b) trial.

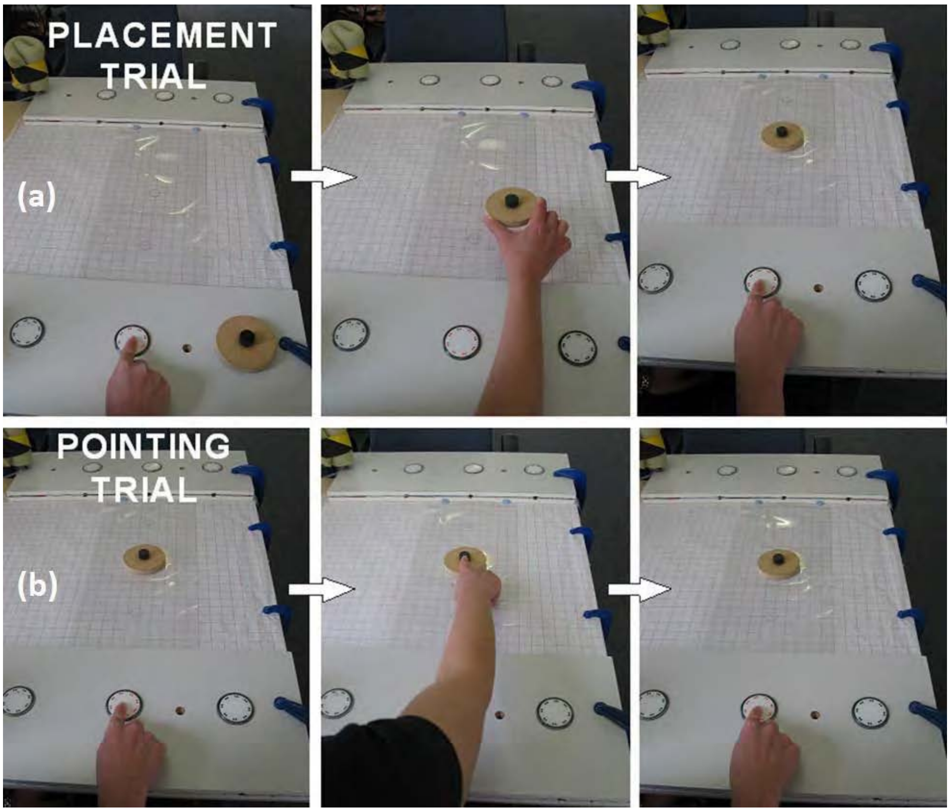
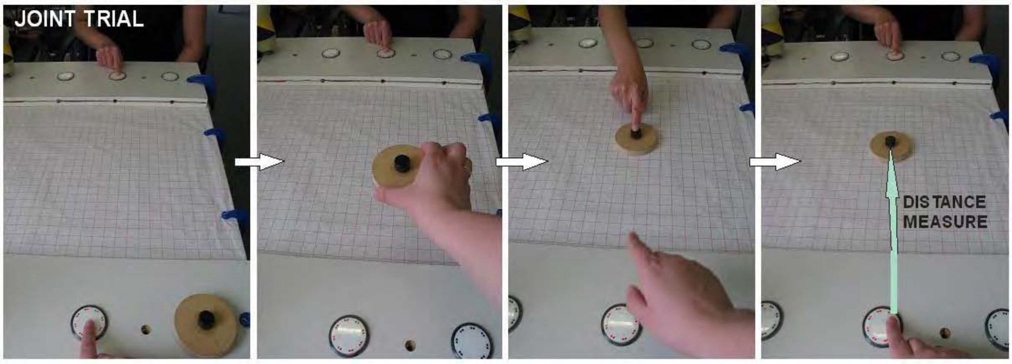


Figure 4.3 Example of a joint interpersonal trial. Note: only in Experiment I could the target pointer begin their movement prior to target placer's return.



4.2.2 Results

4.2.2.1 Interpersonal placement trials

A one-way within-participants repeated-measures ANOVA was performed using the average placement distances for each of the five different target sizes recorded from each participant. Four trials (0.5% of data) were discarded due to equipment failure. The difference in placement distance across the different target sizes narrowly missed significance $F(1.79, 26.79) = 3.26$, $p = .06$, $\eta_p^2 = .18$ (Figure 4.4). In line with the prediction that placing distance might vary linearly with target size, the linear fit of the data was investigated. However, this revealed no significant linear trend $F(1,15) = 3.53$, $p > .05$, $\eta_p^2 = .19$.

Additionally, for each participant a linear regression was performed on their average placing distance at each of the different target sizes (treated as a continuous variable) to obtain the beta slope coefficients (Table 4.1, Figure 4.5). Negative slope coefficients indicated an inverse relationship between the displacement size and target size (e.g., larger displacements for smaller targets). Of the coefficients obtained, the four that differed significantly from zero were those which showed a negative relationship between target and placement distance. Furthermore, to test whether the predicted negative relationship effect was present at the group level, a non-parametric (Skewness: -2.92, *SE* = 0.56) Wilcoxon Signed Ranks Test was conducted on obtained slope coefficients. This indicated that as a whole group, coefficients differed significantly from zero in the negative direction *Z*(-2.25), *p* < .05 (Median = -.08).

Figure 4.4 Experiment I: Average placement distances across all target sizes.

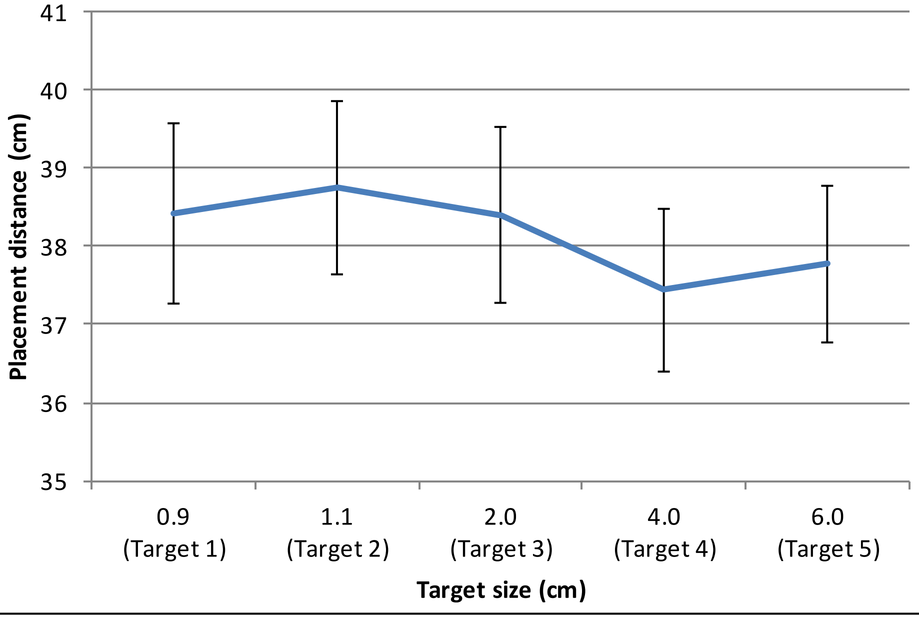


Figure 4.5 Experiment I: Slope coefficients resulting from the regression of placing distance versus target size calculated individually for each participant. * Indicates here the coefficient as significantly different from zero.

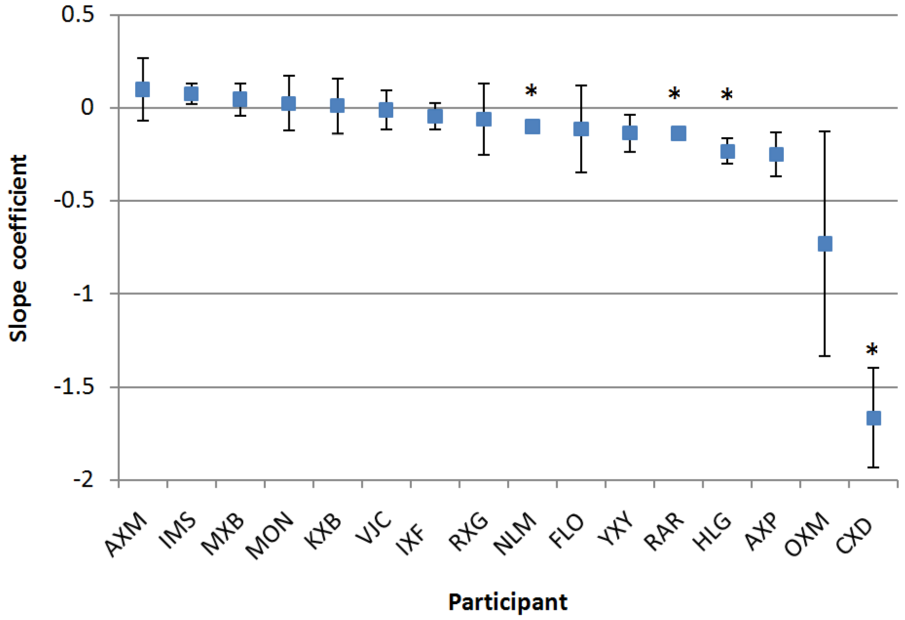


Table 4.1 Slope coefficients (b) obtained from the regression of placing distance (in interpersonal trials) versus target size calculated individually for each participant across Experiments I, II and III.

Table 4.1	Experiment I			Experiment II			Experiment III		
	Ppt	Slope (b)	Std error	Ppt	Slope (b)	Std error	Ppt	Slope (b)	Std error
1	AXM	0.10	0.17	SXS	0.33	0.13	TXR	1.03	0.53
2	IMS	0.08	0.06	VXM	0.23	0.24	CKG	0.57*	0.12
3	MXB	0.05	0.09	CXT	0.12	0.06	JXB	0.16	0.16
4	MON	0.02	0.15	GLI	0.08	0.12	SKH	0.11	0.13
5	KXB	0.01	0.15	TXM	0.08	0.26	OXM	0.10	0.16
6	VJC	-0.01	0.10	VRP	0.02	0.06	NIG	0.08	0.08
7	IXF	-0.05	0.07	EJE	-0.01	0.07	IXS	0.04	0.14
8	RXG	-0.06	0.19	HXC	-0.01	0.21	LXS	-0.56	0.47
9	NLM*	-0.10	0.02	STH	-0.02	0.26	MXM	-0.89	0.15
10	FLO	-0.11	0.23	HXN	-0.03	0.19	AXO	-2.57*	0.21
11	YXY	-0.14	0.10	JPK	-0.03	0.06	SXD2	-4.01*	0.58
12	RAR*	-0.14	0.03	LXS	-0.03	0.06	DXB	-7.10*	0.72
13	HLG*	-0.23	0.07	IXC	-0.04	0.09			
14	AXP	-0.25	0.12	SXW	-0.05	0.95			
15	OXM	-0.73	0.60	SWC	-0.06	0.08			
16	CXD*	-1.67	0.27	KXC	-0.10	0.15			
17				HJK	-0.11	0.29			
18				CXH*	-0.11	0.03			
19				LXB	-0.13	0.12			
20				SXD*	-0.28	0.05			
21				RXW	-0.29	0.15			
22				IAC	-0.48	0.41			
23				BXW	-1.18	0.56			
24				SXC*	-2.77	0.63			
Average		**-0.20**	**0.15**		**-0.20**	**0.22**		**-1.09**	**0.29**
Overall average slope across Experiments I, II & III: -0.41 (*SE* = 0.21) * Indicates a coefficient is significantly different from zero (p < .05)									

4.2.2.2 Baseline trials

In order to elucidate further information which might help explain the pattern of results observed in the joint placing trials, behaviour from the baseline conditions was investigated. Specifically, participants' adherence to Fitts' Law during individual performance was probed.

For each participant, the MTs for the five repetitions of each of the 15 ID conditions (3 target distances × 5 target sizes) were averaged and subjected to a 2 (trial type: placing or pointing) × 3 (target distance: Distance 1, 20.2 cm; Distance 2, 34.2 cm; Distance 3, 48.2 cm) × 5 (target size: Target 1, 0.9 cm; Target 2, 1.1 cm; Target 3, 2.0 cm; Target 4, 4.0 cm; Target 5, 6.0 cm) repeated-measures ANOVA. The ANOVA revealed a significant main effect of trial type, $F(1, 15) = 324.80$, $p < .001$, $\eta_p^2 = .96$. The average MTs for placement trials (μ = 1.24 s, *SE* = 0.04) were noticeably longer than those of pointing trials (μ = 0.87 s, *SE* = 0.03). This result can be explained by the additional movement component required during placement trials to initially pick up the target from its home location prior to its placement on the board. A significant main effect of target distance was found (Figure 4.6), $F(2, 30) = 140.22$, $p < .001$, $\eta_p^2 = .90$, such that the closer a marker was to the participant, the shorter the time required to move towards it. MTs averaged across both trial types for movement to Distance 1 (μ = 0.91 s, *SE* = 0.03) were quicker than to Distance 2 (μ = 1.05 s, *SE* = 0.03) which in turn were quicker than to Distance 3 (μ = 1.20 s, *SE* = 0.04), corroborated with Bonferroni pairwise comparisons (all $p < .001$).

The main effect of target size was also found to be significant, $F(4, 60) = 9.10$, $p < .001$, $\eta_p^2 = .38$ (Figure 4.7). MTs averaged across both trial types for the different target sizes were found to be as follows: Target 1 μ = 1.07 s (*SE* = 0.03), Target 2 μ = 1.06 s (SE = 0.03), Target 3 μ = 1.06 s (SE = 0.04), Target 4 μ = 1.04 s (*SE* = 0.03) and Target 5 μ = 1.03 s (*SE* =

0.03). Bonferroni pairwise comparisons revealed significantly shorter MTs between the largest Target 5 when compared against smaller Targets 1 ($p < .001$), 2 ($p < .05$) and 3 ($p < .01$).

Figure 4.6 Experiment I: Average MTs for the different target distances.

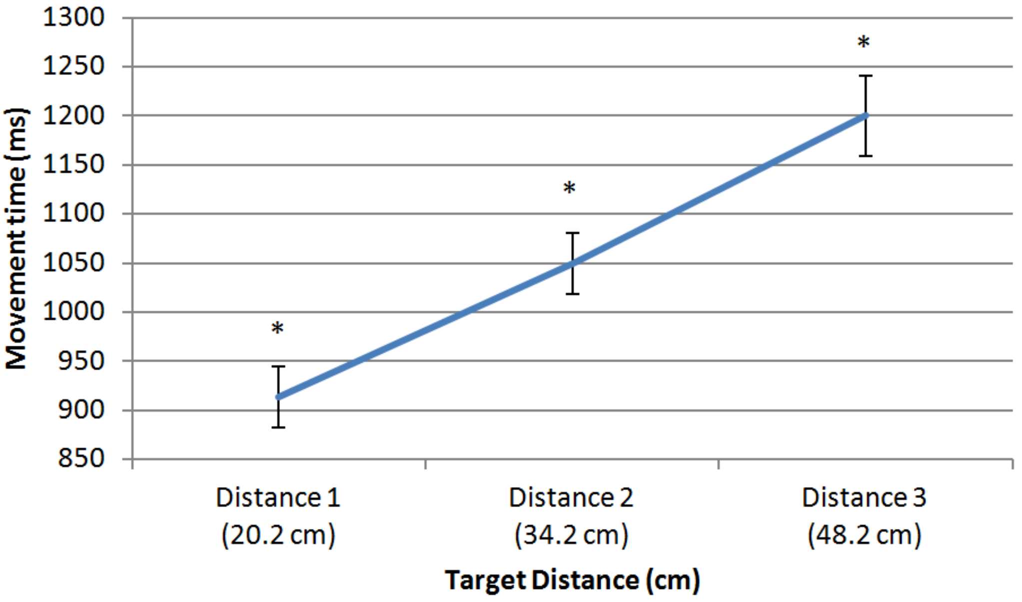
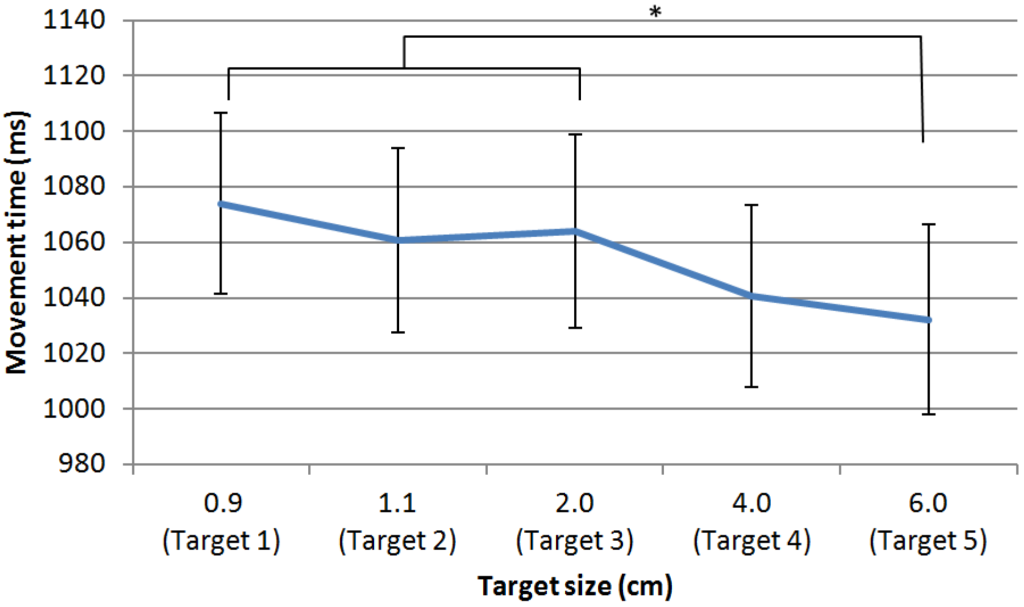


Figure 4.7 Experiment I: Average MTs for the different target sizes.



The only significant interaction found was between trial type and target size *F*(4, 60) = 12.29, $p < .001$, $\eta_p^2 = .45$ (Figure 4.8). To interpret this interaction, simple effects analyses were employed. This revealed target size only had an influence on pointing trials *F*(4, 12) = 22.85, $p < .001$, $\eta_p^2 = .88$. Bonferroni comparisons for pointing trials unveiled significantly shorter MTs between the largest Target 5 when compared against the smaller Targets 1, 2 and 3 (all $p < .001$). Reliably shorter MTs were also noted between Target 4 when compared against Target 1 ($p < .01$) and Target 2 ($p < .05$). The effect of trial type on target size was also significant and consistently demonstrated that regardless of target size, MTs were larger for placing trials compared to pointing trials (all $p < .001$). The interaction between trial type and target size therefore appeared to be due to larger MTs for placing trials which required the participant to first pick up the target, combined with the generally shorter MTs for the largest Targets 4 and 5 in pointing trials.

Finally, to test the baseline performance against pointing performance index of difficulties, overall MT was plotted against ID (Figure 4.9). This showed a strong violation of the expected linear relationship.

Figure 4.8 Experiment I: The interaction between trial type and target size.

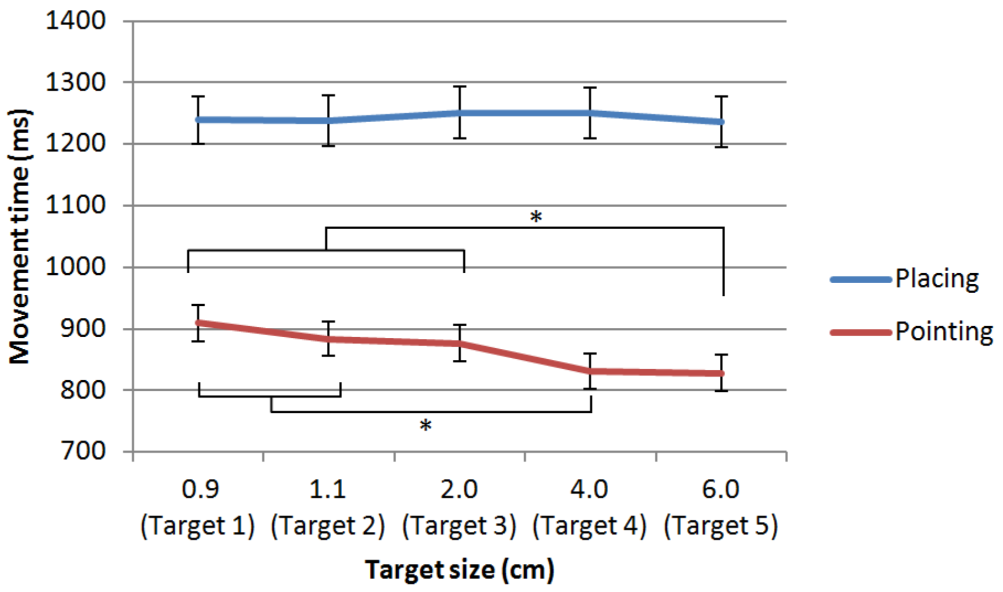
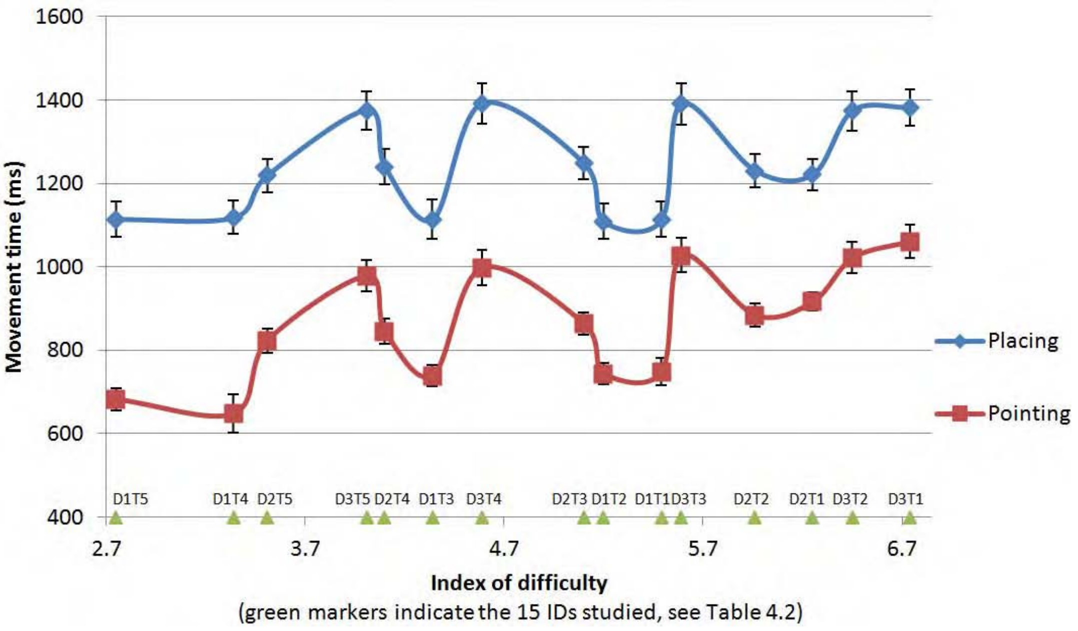


Figure 4.9 Experiment I: Average MTs for baseline placing and pointing trials in ascending order of index of difficulty.



4.3 Experiment II: New set-up

4.3.1 Method

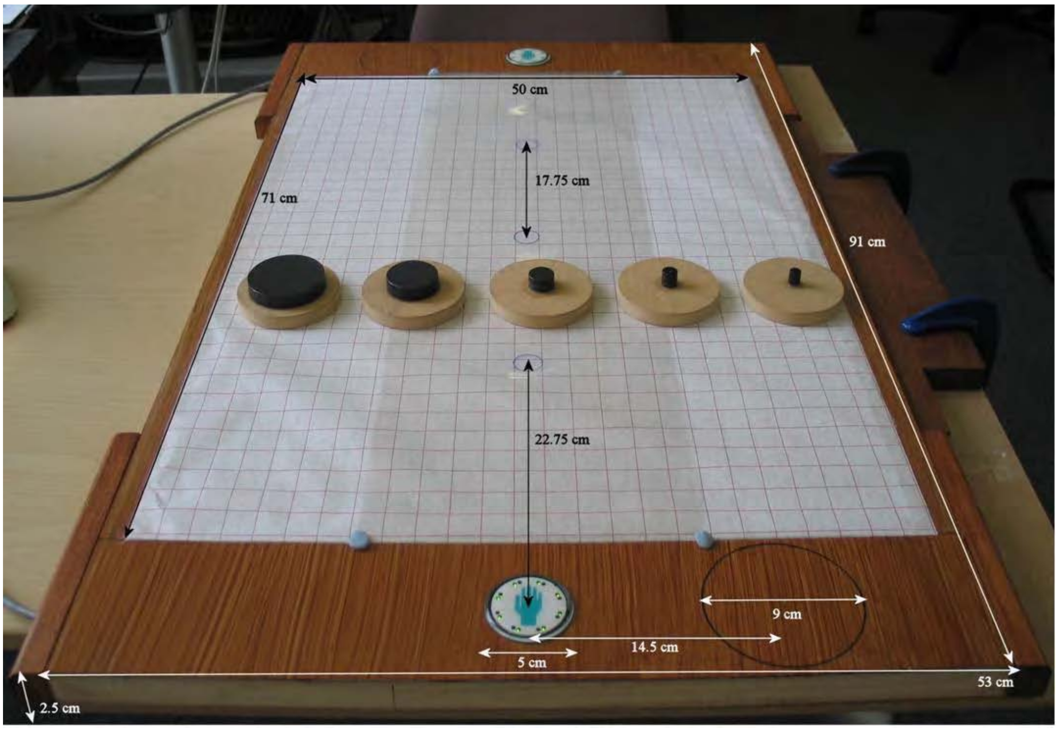
4.3.1.1 Participants

Twenty-four healthy participants (16 female) with a mean age of 20.0 years (*SD* = 1.4 years) were recruited from the University of Birmingham. All participants were right-handed (self-reported) and had normal or corrected-to-normal vision. Compensation of cash or credits remained unchanged.

4.3.1.2 Apparatus and Materials

The button panels used in Experiment I were on loan. Experiment II was therefore conducted with a second set, with small differences in the overall dimensions of the set-up (see Appendix two).

Figure 4.10 Experiment II: Set-up and targets.



4.3.1.3 Design and Procedure

The procedure remained largely unchanged from Experiment I with only a few modifications reported below. As before, participants were tested individually in Session 1 and in pairs in Session 2.

4.3.1.3.1 Session 1

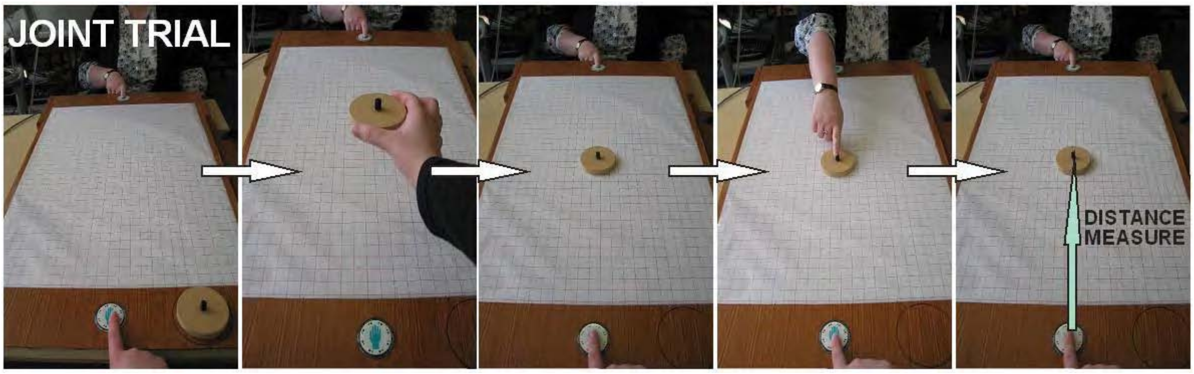
The only change was that now instead of placing targets down on the right unused button (no longer present), the experimenter would place each target down in a circle of 9 cm diameter drawn at either end of the board and whose centre was located 14.5 cm to the right of the button centre on that side of the board.

4.3.1.3.2 Session 2

Participants returned for Session 2 between 3 and 14 days after Session 1. In total, 12 participant pairs were tested. As previously, participants were paired with another same-sex partner roughly matched for arm length. In the worst matched case, there was a discrepancy of approximately 5 cm in arm length between participants, whereas in all other pairings arm length differed by roughly 1 cm (μ = 1.04 cm). Instructions for the joint task were as before except the phrasing was slightly changed to: "Your mutual aim is to *work together* to perform both of these tasks as QUICKLY and as ACCURATELY as possible". It was thought this wording would emphasize the need to be cooperative.

The only other difference from Experiment I was that in Session 2, target pointers now had to wait for the placer to have returned their finger to their starting position before they could begin making their own movement (Figure 4.11). This had not been necessary previously, although most participants had spontaneously done so. This change in instruction was implemented to encourage pointers to pay closer attention to the placer's movements before initializing their own movement. The brief tone elicited as a button was released or pressed meant that the placer's return tone could serve as a cue for the pointer to begin their own movement. A trial thus started at the onset of the placer's movement and finished with the offset of the pointer's movement. After every trial a manual measurement of the displacement of the target was taken. After debriefing, one participant pair indicated that they were friendly, but they did not know each other well.

Figure 4.11 Example of a joint interpersonal trial in Experiment II & III. Here target pointers had to wait for the placer's return prior to initiating their own movement. In Experiment III a motion sensor was secured to each participant's right index finger.



4.3.2 Results

4.3.2.1 Interpersonal placement trials

Analyses were unchanged from those described in Experiment I. No significant differences in the placement distances was observed across the different target sizes, $F(2.17, 49.92) = 1.65$, $p > .05$, $\eta_p^2 = .07$ (Figure 4.12). The average displacement measurements for the different target sizes were as follows: Target 1 $\mu = 50.74$ cm ($SE = 1.42$), Target 2 $\mu = 50.64$ cm ($SE = 1.32$), Target 3 $\mu = 50.28$ cm ($SE = 1.14$), Target 4 $\mu = 50.28$ cm ($SE = 1.18$) and Target 5 $\mu = 49.55$ cm ($SE = 1.25$). The linear fit of the data also indicated no significant linear trend between placing distance and target size $F(1,23) = 2.26$, $p > .05$, $\eta_p^2 = .09$. As in Experiment I, for each participant a linear regression was performed on their average placing distance for each target size so as to acquire the beta slope coefficients (Table 4.1, Figure 4.13). Of the coefficients retrieved, the three that differed significantly from zero showed a negative relationship between target and placement distance, as hypothesized. At the group level, a non-parametric (Skewness: -3.56, *SE* = 0.47) Wilcoxon Signed Ranks Test marginally missed significance *Z*(-1.96), *p* = .05. However, there appeared to be a trend for coefficients which differed significantly from zero in the negative direction *Z*(-2.25), *p* < .05 (Median = -.04).

Figure 4.12 Experiment II: Average placement distances across all target sizes.

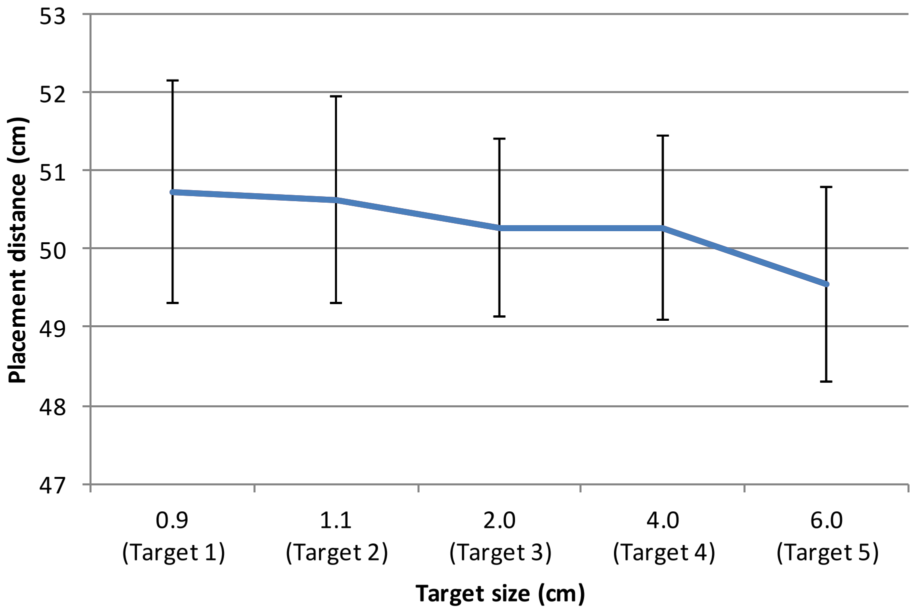
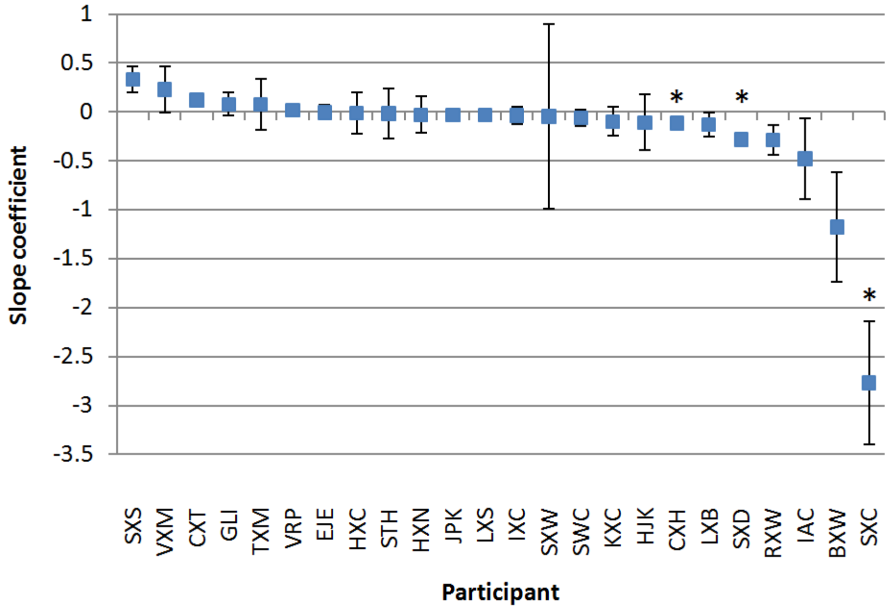


Figure 4.13 Experiment II: Slope coefficients resulting from the regression of placing distance versus target size, calculated individually for each participant. * Indicates here the coefficient as significantly different from zero.



4.3.2.2 Baseline trials

Identical analyses were performed to those in Experiment I. A significant main effect of trial type was observed, $F(1, 23) = 567.68$, $p < .001$, $\eta_p^2 = .96$. Average MTs for placement trials ($\mu = 1.22$ s, $SE = 0.03$) were considerably longer than those of pointing trials ($\mu = 0.86$ s, $SE = 0.03$). This no doubt reflected the additional movement component involved in having to pick up the target first during placing trials.

A significant main effect of target distance was also found, $F(2, 46) = 166.52$, $p < .001$, $\eta_p^2 = .88$ (Figure 4.14). Average MTs for the nearest Distance 1 ($\mu = 0.87$ s, $SE = 0.02$) were significantly shorter than those of intermediate Distance 2 ($\mu = 1.03$ s, $SE = 0.03$) which in turn were shorter than those of the furthest Distance 3 ($\mu = 1.21$ s, $SE = 0.04$), corroborated with pairwise comparisons (all $p < .001$).

The main effect of target size was also significant, $F(2.39, 55.03) = 16.88$, $p < .001$, $\eta_p^2 = .42$ (Figure 4.15). Average MTs for the different target sizes were as follows: Target 1 $\mu = 1.05$ s ($SE = 0.03$), Target 2 $\mu = 1.05$ s ($SE = 0.03$), Target 3 $\mu = 1.05$ s ($SE = 0.03$), Target 4 $\mu = 1.03$ s ($SE = 0.03$) and Target 5 $\mu = 1.02$ s ($SE = 0.03$). Bonferroni pairwise comparisons uncovered reliable differences in MTs between the largest Target 5 compared against the smaller Targets 1, 2, 3(all $p < .001$) and 4 ($p < .05$). Reliable differences were also noted for Target 4 when compared against Targets 1 and 2 (both $p < .01$). In each significant case reported the larger of the two targets led to smaller MTs.

Figure 4.14 Experiment II: Average MTs for the different target distances.

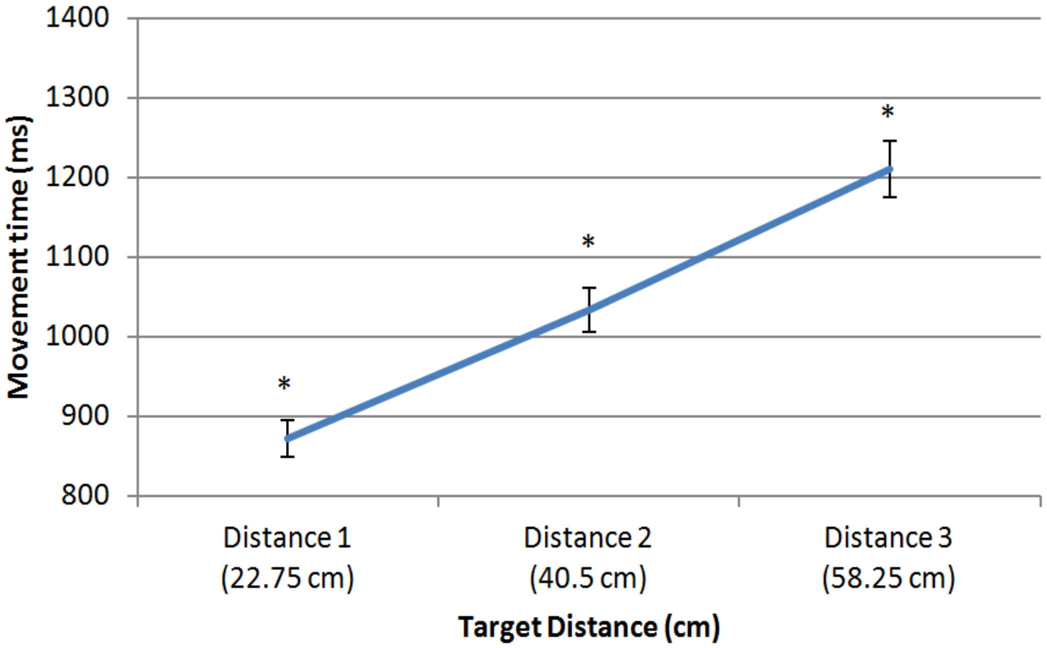
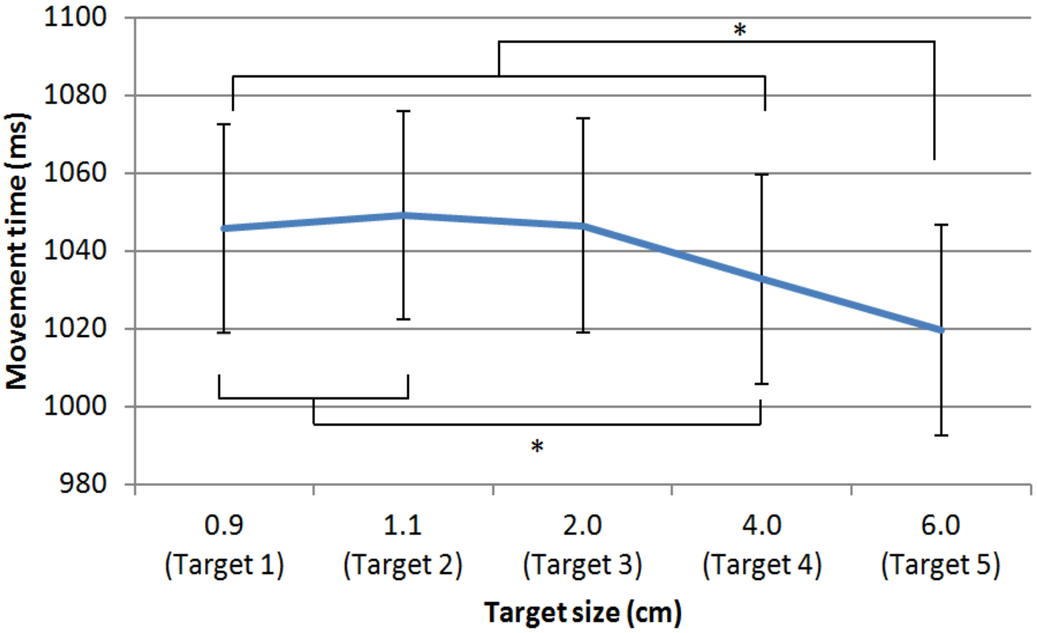


Figure 4.15 Experiment II: Average MTs for the different target sizes.



Two interactions were also observed. The first of these was between trial type and target size $F(2.86, 65.75) = 28.05$, $p < .001$, $\eta_p^2 = .55$ (Figure 4.16). The second interaction noted was between target distance and target size, $F(8,184) = 2.07$, $p < .05$, $\eta_p^2 = .08$ (Figure 4.17).

To clarify the nature of these interactions, simple effects analyses were carried out. Doing this revealed that target size had an influence on both placing $F(4, 20) = 4.91$, $p < .01$, $\eta_p^2 = .50$ and pointing $F(4, 20) = 30.46$, $p < .001$, $\eta_p^2 = .86$ trials. However, Bonferroni comparisons for placing trials only established one significant difference between target sizes, which showed larger MTs for Target 4 when compared against the smaller Target 1 ($p < .05$). By contrast, Bonferroni comparisons for pointing trials unveiled significantly shorter MTs for the largest Target 5 when compared against the smaller Targets 1 ($p < .001$), 2 ($p < .001$), 3 ($p < .001$) and 4 ($p < .05$). Significantly shorter MTs were also noted for Target 4 when compared against the smaller Targets 1, 2 and 3 (all $p < .001$). The effect of trial type on target size was significant also and showed that, irrespective of target size, MTs were always larger for placing trials compared to pointing trials (all $p < .001$). The interaction between trial type and target size therefore appeared to be due to larger MTs for placing trials which required the participant to first pick up the target, combined with the generally shorter MTs for Target 1 in placing trials and Targets 4 and 5 in pointing trials.

In addition, simple effects analyses revealed that target size had an influence on movements made both to the intermediate target distance set at Distance 2 $F(4, 20) = 7.65$, $p < .01$, $\eta_p^2 = .61$ and to movements made to the furthest target distance set at Distance 3 $F(4, 20) = 8.48$, $p < .001$, $\eta_p^2 = .63$. For the target distance set at Distance 2, Bonferonni comparisons unearthed significantly shorter MTs for Target 5 when compared against the smaller Targets 1 ($p < .001$), 2 ($p < .01$), 3 ($p < .01$) and 4 ($p < .01$). Similarly, for the target distance set at Distance 3, Bonferroni comparisons uncovered significantly shorter MTs for Target 5 when compared against the smaller Targets 1, 2 and 3 (all $p < .01$). The effect of target distance on target size was also significant and revealed that irrespective of target size, MTs for movements made to the closest Distance 1 were significantly shorter than those made to the intermediate Distance 2 which in turn were shorter than those movement made to the furthest Distance 3 (all comparisons $p < .001$). Thus, the interaction between target distance and target size appeared to demonstrate that whilst average MTs increased as the target distance increased, the MT advantage for the largest Target 5 only presented itself at the intermediate and far target distances.

Taken together, the results suggest that average MTs were largely unaffected by target size during placement trials, whereas during pointing trials there was a significant trend in the direction of shorter MTs for larger compared to smaller targets. Furthermore, to test the baseline performance against pointing performance index of difficulties, overall MT was plotted against ID (Figure 4.18) which revealed a strong violation of the linear relationship expected by Fitts' Law.

Figure 4.16 Experiment II: The interaction between trial type and target size.

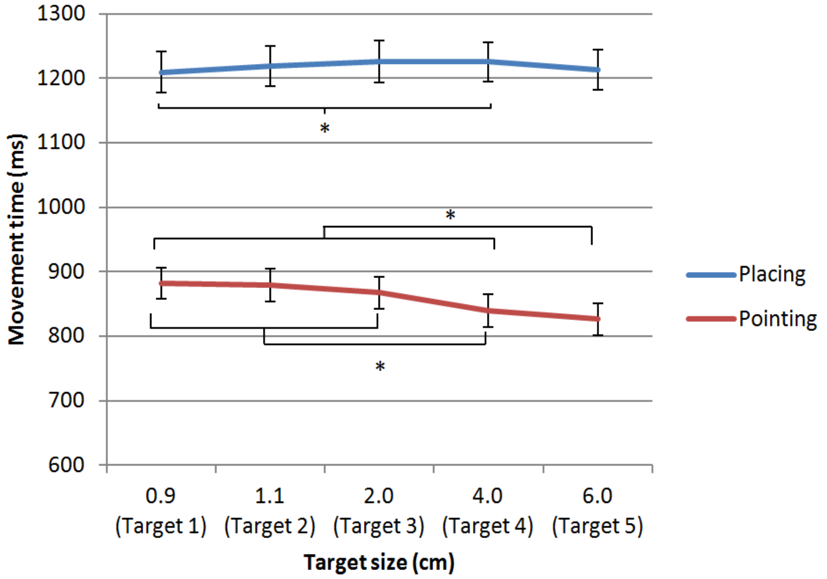


Figure 4.17 Experiment II: The interaction between target distance and target size.

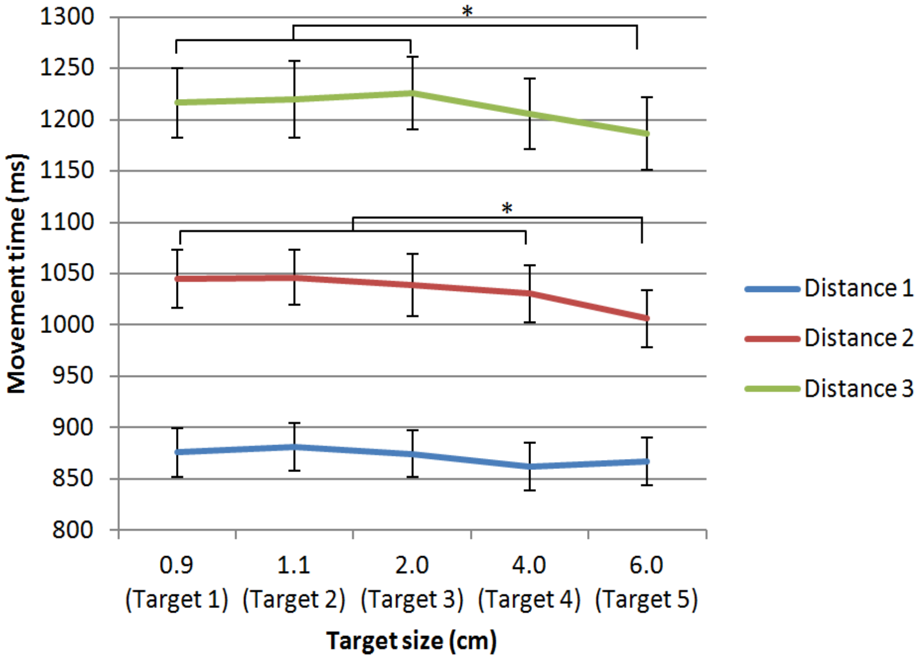
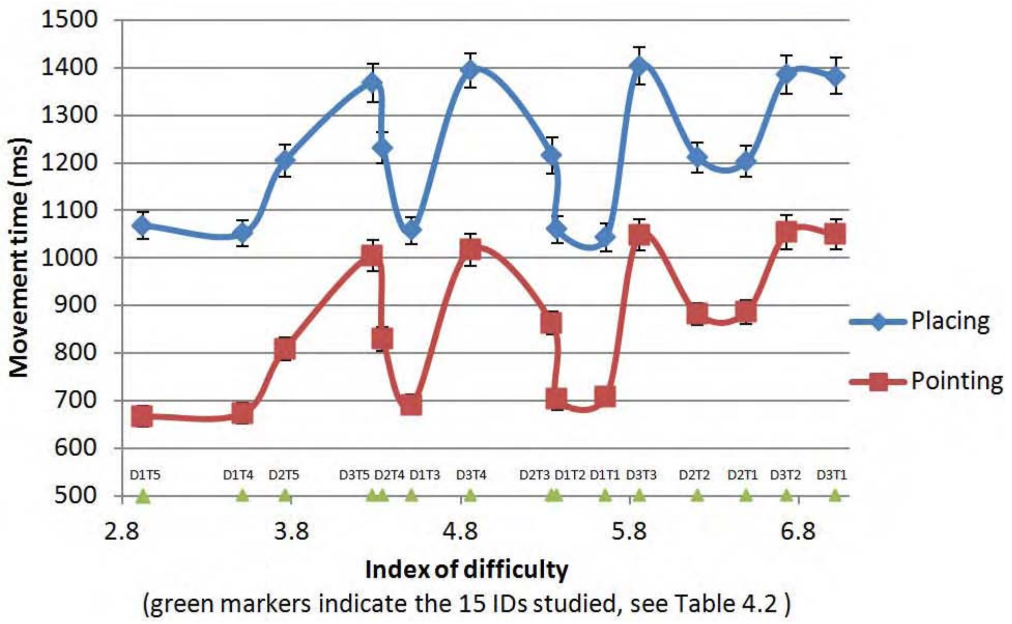


Figure 4.18 Experiment II: Average MTs for baseline placing and pointing trials in ascending order of index of difficulty.



4.4 Experiment III: New set-up with motion tracking

4.4.1 Method

4.4.1.1 Participants

Twelve healthy participants (8 female) with a mean age of 17.0 years (*SD* = 0.4 years) were recruited from students at a local sixth form college who were visiting the University of Birmingham psychology department. They were all right handed (self-reported) and had normal or corrected-to-normal vision. No compensation was offered.

4.4.1.2 Apparatus and Materials

The apparatus was virtually identical to that of Experiment II. The principal difference to the set-up was the addition of motion tracking equipment to avoid the need for a manual measurement of the target placer's displacement of each target and targets had now also been equalized for weight (65.7 g) (see Appendix three).

Figure 4.19 Experiment III: Set-up with motion tracking and no grid.

4.4.1.3 Design and Procedure

The experiment was a within-participants design. Unlike previously, now both the baseline (solo) and joint (interpersonal) parts of the task were tested within the same session, lasting approximately 50 minutes.

4.4.1.3.1 Baseline pointing trials

In the baseline part of the task, only pointing movements were recorded. This was due to time constraints in collecting data from visiting students. The transparency was fixed into place so that participants could see the three circles on the workspace in front of them. During this baseline task the experimenter placed down one of the five possible targets so that it fully covered one of the markers on the transparency as centrally as possible. Targets were selected in pseudo-randomized order of size. Marker location was blocked so that participants performed 15 pointing trials (a third of trials) on one marker before moving on to the next marker. The blocks were randomized.

To begin a trial, the participant rested the index finger of their right hand (equipped with the motion sensor) on the active illuminated button. Shortly afterwards a series of three tones emanating from a computer speaker would be sounded. The third tone acted as the go signal for the participant to release their button, rapidly reach out to and touch the black target on the disk placed before them with the tip of their index finger, before once again returning their finger to the active button. Participants were given the same speed and accuracy instructions emphasized in Experiments I and II. After each pointing trial had concluded, the experimenter removed the target from the workspace and replaced it with a new target. There were three repetitions of each of the five target sizes at each of the three marker locations (5 × 3 × 3) so that in total each participant performed 45 pointing trials. In contrast to Experiments I and II, participants performed the baseline portion of the task in the presence of each other so that whilst one participant performed the task, the other simply watched. The experimenter randomly selected who in the pair would commence.

4.4.1.3.2 Part 2: Interpersonal placement trials

Participants performed the joint part of the task with another same-sex participant. As participants were collected via opportunity sample, they could not be appropriately matched for arm length ahead of the joint task. In the worst matched case there was a discrepancy of approximately 15 cm in arm length between participants, whereas in the best cases arm length differed by approximately 1 cm (μ = 4.83 cm). In total six participant pairs were tested. Instructions were identical to those of Experiment II. In total there were 120 joint trials and participants exchanged roles as target placer (60 trials) and target pointer (60 trials) half way through, although remaining in the same seat for both roles. Participants refrained from communicating with their task partner during testing.

Procedure was identical to Experiment II, except that now no manual measurement of placing distance was necessary, as motion tracking was employed to measure displacements discretely. As all participants attended college together, most task partners had met before and the majority of pairs reported that they were friendly with each other.

4.4.2 Results

4.4.2.1 Interpersonal placement trials

Analyses remained unchanged from Experiments I and II. Placement distances for the different target sizes did not differ significantly, $F(1.13, 12.42) = 2.11$, $p > .05$, $\eta_p^2 = .16$ (Figure 4.20). The average displacement measurements for the different target sizes were found to be as follows: Target 1 μ = 60.38 cm (*SE* = 2.57), Target 2 μ = 59.39 cm (*SE* =

2.92), Target 3 μ = 58.60 cm (*SE* = 2.54), Target 4 μ = 56.62 cm (*SE* = 3.56) and Target 5 μ = 54.81 cm (*SE* = 4.16).

The linear fit of the data also indicated no significant linear trend between placing distance and target size $F(1,11) = 2.32$, $p > .05$, $\eta_p^2 = .17$. Again, for each participant a linear regression was implemented on their average placing distance for each target size to attain the slope coefficients (Table 4.1, Figure 4.21). Of the coefficients calculated, three showed a negative relationship between target and placement distance, whilst one participant showed a positive relationship between those variables. No significant differences were noted across the whole group as indicated by a non-parametric (Skewness: -1.84, *SE* = .64) Wilcoxon Signed Ranks Test *Z*(-0.63), $p > .05$ (Median = .06).

Figure 4.20 Experiment III: Average placement distances across all target sizes.

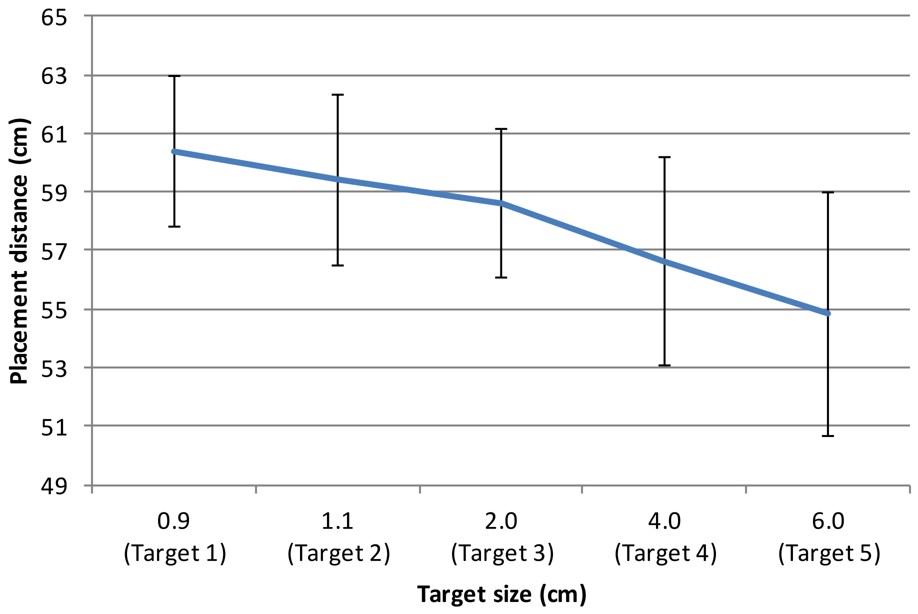
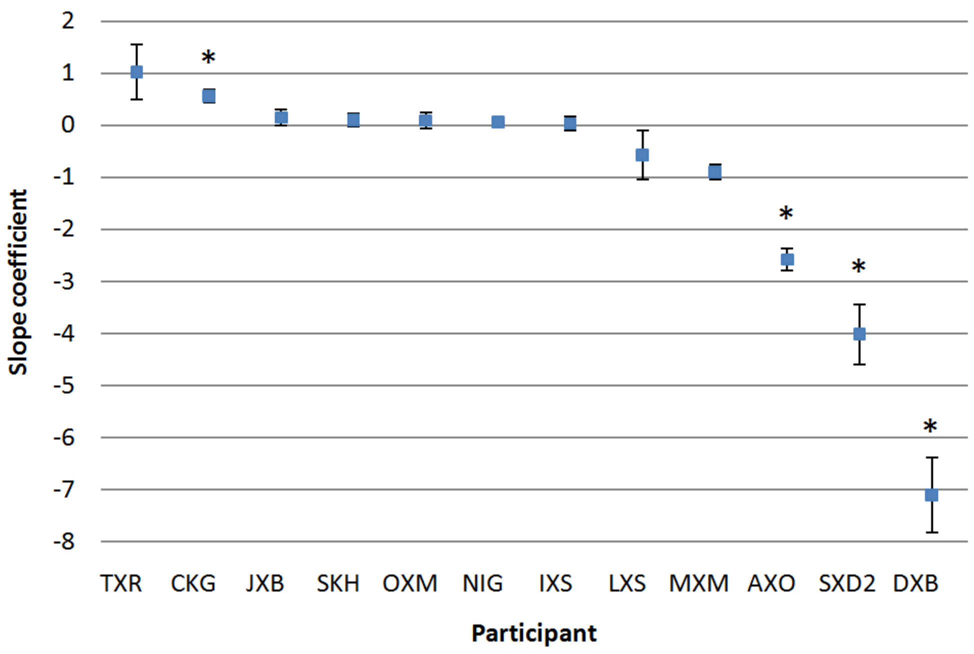


Figure 4.21 Experiment III: Slope coefficients resulting from the regression of placing distance versus target size, calculated individually for each participant. * Indicates here the coefficient as significantly different from zero.



4.4.2.2 Baseline trials

To further shed light on behaviour during the interpersonal placing trials, baseline behaviour was examined. In Experiment III, there were no baseline placing trials, thus only pointing trials were analyzed. MTs for the three repetitions of each of the 15 ID conditions were averaged for each participant and these averages were subjected to 3 (target distance) × 5 (target sizes) repeated-measures ANOVA.

The ANOVA revealed a significant main effect of target distance, $F(2, 22) = 70.04$, $p < .001$, $\eta_p^2 = .86$ where average MTs for the closest Distance 1 ($\mu = 0.87$ s, $SE = 0.04$) were shorter than those of the intermediate Distance 2 ($\mu = 1.06$ s, $SE = 0.05$), which in turn were shorter than those of the furthest Distance 3 (μ = 1.36 s, *SE* = 0.07), confirmed using pairwise comparisons (all $p < .001$) (Figure 4.22).

The main effect of target size was also significant, $F(1.77, 19.41) = 18.63$, $p < .001$, $\eta_p^2 = .63$ (Figure 4.23). The average MTs for the different target sizes were found to be as follows: Target 1 μ = 1.15 s (*SE* = 0.04), Target 2 μ = 1.13 s (*SE* = 0.05), Target 3 μ = 1.11 s (*SE* = 0.05), Target 4 μ = 1.05 s (*SE* = 0.06) and Target 5 μ = 1.03 s (*SE* = 0.05). Pairwise comparisons revealed reliably shorter MTs for the largest Target 5 compared against the smaller Targets 1 ($p < .01$), 2 ($p < .001$) and 3 ($p < .01$). This was also true for Target 4 compared against the smaller Targets 1 ($p < .05$), 2 ($p < .01$) and 3 ($p < .01$). The interaction between target distance and target size was not significant, $F(8, 88) = 1.86$, $p > .05$, $\eta_p^2 = .15$.

Finally, baseline performance MT was plotted against pointing performance index of difficulties which revealed a strong violation of the expected linear relationship (Figure 4.24).

Figure 4.22 Experiment III: Average MTs for the different target distances.

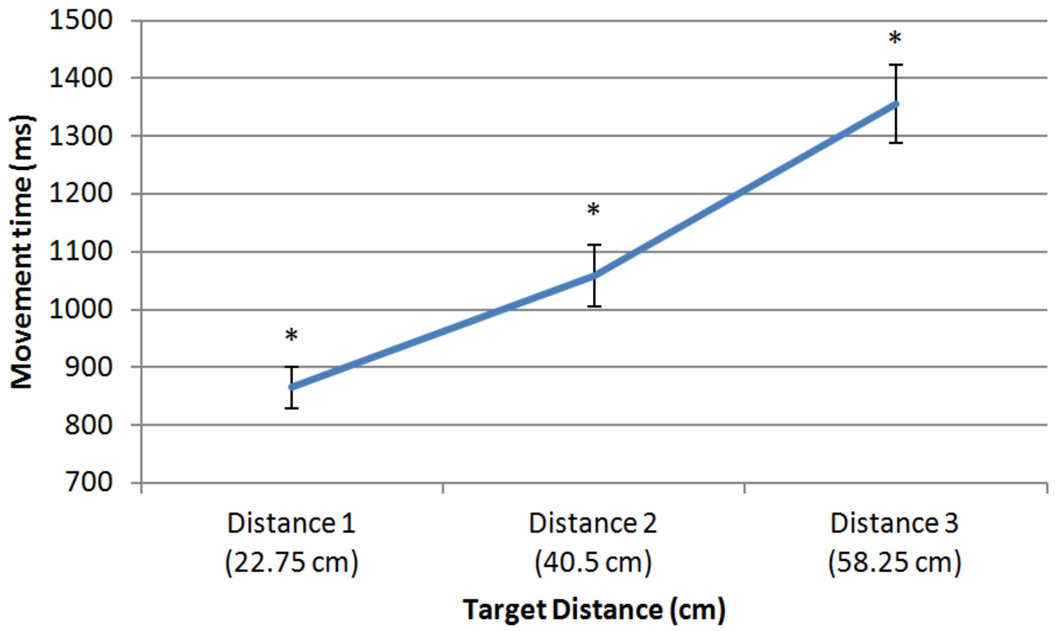


Figure 4.23 Experiment III: Average MTs for the different target sizes.

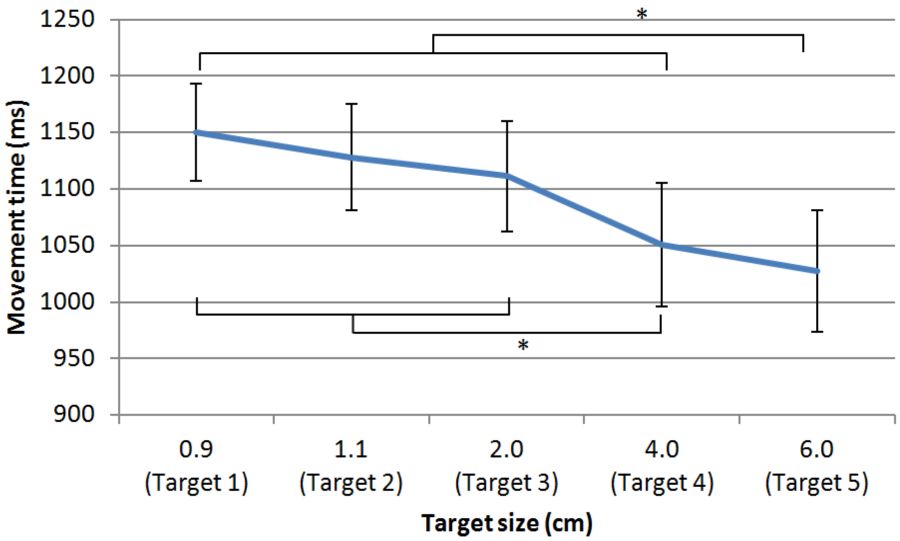
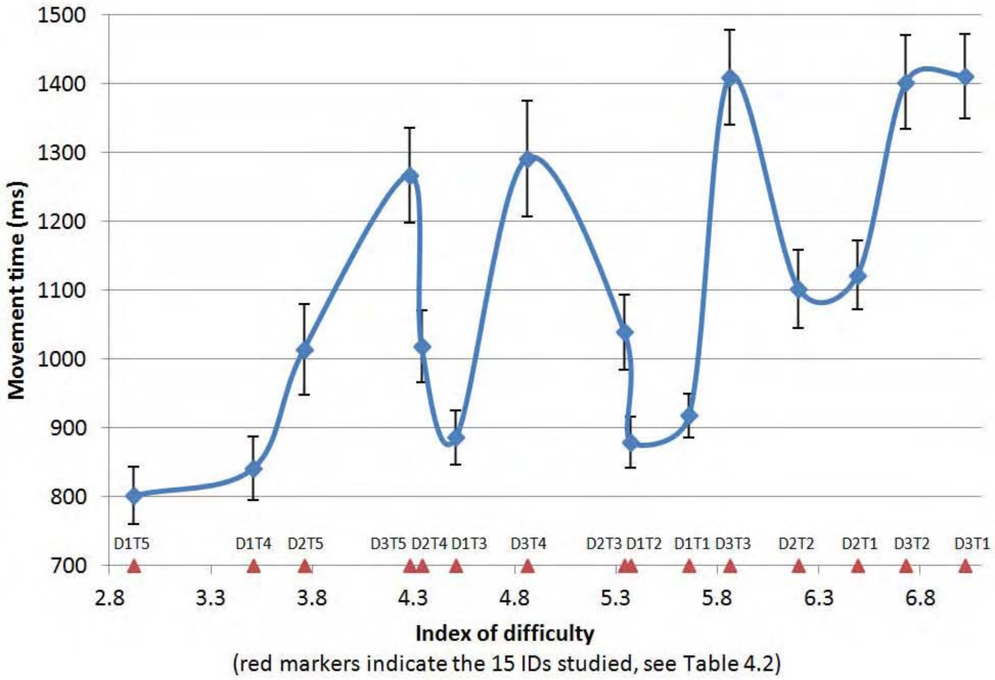


Figure 4.24 Experiment III: Average MTs for baseline pointing trials in ascending order of index of difficulty.



4.5 Further analyses of Experiments I, II and III

4.5.1 Examination of pointing movements in Experiments I and II

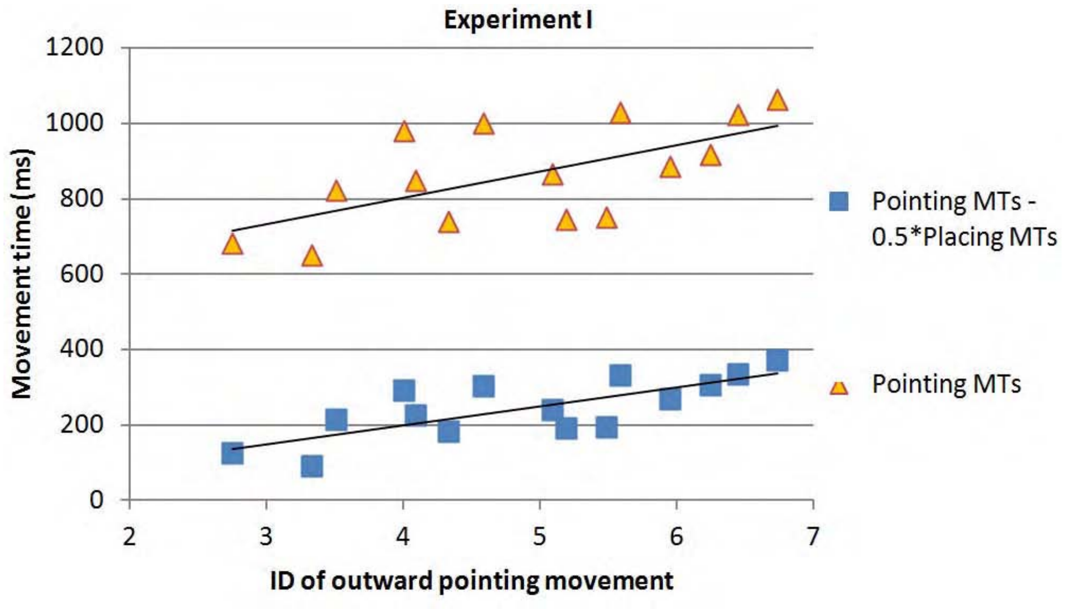
To examine the poor linear fit based on pointing task ID (Figures 4.9, 4.18, 4.24), placing and pointing movements were treated as a combination of a direct outward reach-and-return movement. By envisaging pointing MTs comprising of two parts—the first an outward reach to a target governed by Fitts' Law and the second a return movement to the constant-size starting button—pointing MTs could be predicted from the estimated time to reach that far, using the placing baseline data. Placing movements were effectively treated as two identical outward and return movements and so the time to reach a given distance was estimated at half the overall MT of that trial. The return movements for condition-equivalent placing and pointing trials were proposed to be identical. Hence, by partitioning out the placing MT for the return movement (i.e., half overall placing MT for given distance and target size) from the pointing data, an estimate of the MT to the outward pointing movement could be computed (Note: Experiments III lacked the placing trials to do this).

A linear regression of these MTs against the IDs for only the outward pointing component (Table 4.2) revealed a stronger fit (r^2 = .56 and r^2 = .49 in Experiments I and II, respectively) when compared to the MTs from unaltered pointing MTs (r^2 = .40 and r^2 = .35 in Experiment I and II, correspondingly) (Figure 4.25a, 4.25b). Thus the original pointing MTs were dominated by the return aspect of movement (i.e., the amplitude term from the Fitts equation), weathering the effect of target size on pointing MT.

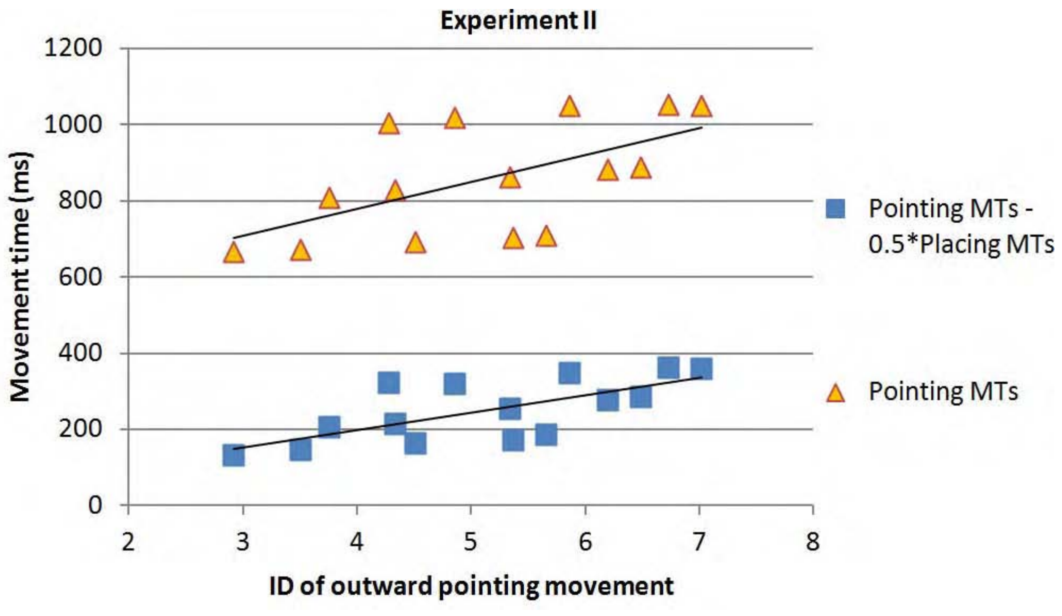
Table 4.2 Index of difficulty values for pointing trials based on the outward reaching component only.

Table 4.2 Calculated from the Fitts equation: ID = $Log_2(2D/W)$ D = amplitude distance	Experiment I			Experiments II and III		
	Distance 1 (20.2 cm)	Distance 2 (34.2 cm)	Distance 3 (48.2 cm)	Distance 1 (22.75 cm)	Distance 2 (40.5 cm)	Distance 3 (58.25 cm)
Target 1 (0.9 cm)	D1T1: 5.49	D2T1: 6.25	D3T1: 6.74	D1T1: 5.66	D2T1:6.49	D3T1: 7.02
Target 2 (1.1 cm)	D1T2: 5.20	D2T2:5.96	D3T2: 6.45	D1T2: 5.37	D2T2: 6.2	D3T2: 6.73
Target 3 (2.0 cm)	D1T3:4.34	D2T3:5.10	D3T3: 5.59	D1T3: 4.51	D2T3:5.34	D3T3: 5.86
Target 4 (4.0 cm)	D1T4:3.34	D2T4:4.10	D3T4: 4.59	D1T4: 3.51	D2T4: 4.34	D3T4: 4.86
Target 5 (6.0 cm)	D1T5:2.75	D2T5:3.51	D3T5: 4.01	D1T5: 2.92	D2T5: 3.76	D3T5: 4.28

Figure 4.25 Average MTs for baseline pointing trials averaged across all participants in Experiments I (a) and II (b).



(a)



(b)

4.5.2 Linear regression

To further explore the data, pointing and placing trials were broken down into basic units (Figure 4.26). The placing trial MT was divided into three submovements (X, Y and Z) whose sum represented an estimate of the total placing movement. These three movements were (1) the reach-to-grasp movement 'X' towards the base of the target (8 cm) located a known distance away from the starting button (either 15 cm away in Experiment I or 14.5 cm away in Experiment II), (2) the movement 'Y' from this target home location to cover the 2 cm marker on the workspace, and (3) the movement 'Z' from the marker back to the starting button (5 cm), known to be at one of three distances during baseline trials (D1, D2 or D3). Crucially, each submovement involved its own ID. The total MT during placing could thus be captured in equation form:

Using Fitts formulation:

$$\mathrm{MT_{placing}} = a_x + b_x \cdot \log_2 \left(\frac{2X}{target\ base\ width}\right) + a_y + b_y \cdot \log_2 \left(\frac{2\sqrt{Z^2 + X^2}}{marker\ width}\right) + a_z + b_z \cdot \log_2 \left(\frac{2Z}{button\ width}\right)$$

Using Shannon formulation where ID = $\mathrm{Log}_2(1+A/W)$ (see MacKenzie, 1989):

$$\mathrm{MT_{placing}} = a_x + b_x \cdot \log_2 \left(1 + \frac{X}{target\ base\ width}\right) + a_y + b_y \cdot \log_2 \left(1 + \frac{\sqrt{Z^2 + X^2}}{marker\ width}\right) + a_z + b_z \cdot \log_2 \left(1 + \frac{Z}{button\ width}\right)$$

All coefficients were assumed to remain invariable across trials (e.g., the initial reach-to-grasp movement X should not change) for a given participant. Furthermore the beta slope values (b) should also have held within each participant allowing the placing equations to be simplified:

$$a_{Fitts} = a_x + b_x \cdot \log_2(\frac{2X}{target\ base\ width}) + a_y + \ a_z$$

$$or\ a_{Shannon} = a_x + b_x \cdot \log_2(1 + \frac{X}{target\ base\ width}) + a_y + \ a_z$$

$$where: b = b_x = b_y = \ b_z \text{ and } a = a_x = a_y = \ a_z$$

$$\mathrm{MT}_{\text{Fitts placing}} = a_{Fitts} + b \cdot \log_2\left(\frac{2\sqrt{Z^2 + X^2}}{marker\ width}\right) + b \cdot \log_2(\frac{2Z}{button\ width})$$

or

$$\mathrm{MT}_{\text{Shannon placing}} = a_{Shannon} + b \cdot \log_2\left(1 + \frac{\sqrt{Z^2 + X^2}}{marker\ width}\right) + b \cdot \log_2(1 + \frac{Z}{button\ width})$$

Similarly, the pointing movement involved two submovements of equal distance (Z) but towards different widths (and hence different IDs): (1) the outward movement 'Z_{out}' (known to be one of three distances: D1, D2 or D3) towards the target (5 known sizes) and (2) the return movement 'Z_{in}' from the target back to the starting button (5 cm). The total MT during pointing in equation form was calculated as follows:

Using Fitts formulation:

$$\mathrm{MT}_{\text{pointing}} = a_z + b_z \cdot \log_2(\frac{2Z_{out}}{target\ width}) + a_z + b_z \cdot \log_2(\frac{2Z_{in}}{button\ width})$$

Similarly simplified to

$$\mathrm{MT}_{\text{Fitts pointing}} = a + b \cdot [\log_2(\frac{2Z_{out}}{target\ width}) + \log_2(\frac{2Z_{in}}{button\ width})]$$

Using Shannon formulation:

$$\mathrm{MT_{pointing}} = a_z + b_z \cdot \log_2(1 + \frac{Z_{out}}{target\ width}) + a_z + b_z \cdot \log_2(1 + \frac{Z_{in}}{button\ width})$$

Similarly simplified to

$$\mathrm{MT_{Shannon\ pointing}} = a + b \cdot [\log_2(1 + \frac{Z_{out}}{target\ width}) + \log_2(1 + \frac{Z_{in}}{button\ width})]$$

For each participant the average MTs for the baseline placement trials corresponding to a recognized ID condition (equivalent to the sum of the IDs across the three submovements) were known, enabling a linear regression to determine each participant's unique slope (b) and y-intercept (a) coefficients for placing in Experiments I and II (placing trials were absent in Experiment III) (Table 4.3). Equally, using the average MTs for the baseline pointing trials corresponding to a recognized ID condition (equivalent to the sum of the IDs across the two submovements) coefficients for pointing were also calculated (Table 4.3).

Figure 4.26 Representation of the three submovements X, Y and Z involved during a placement trial.

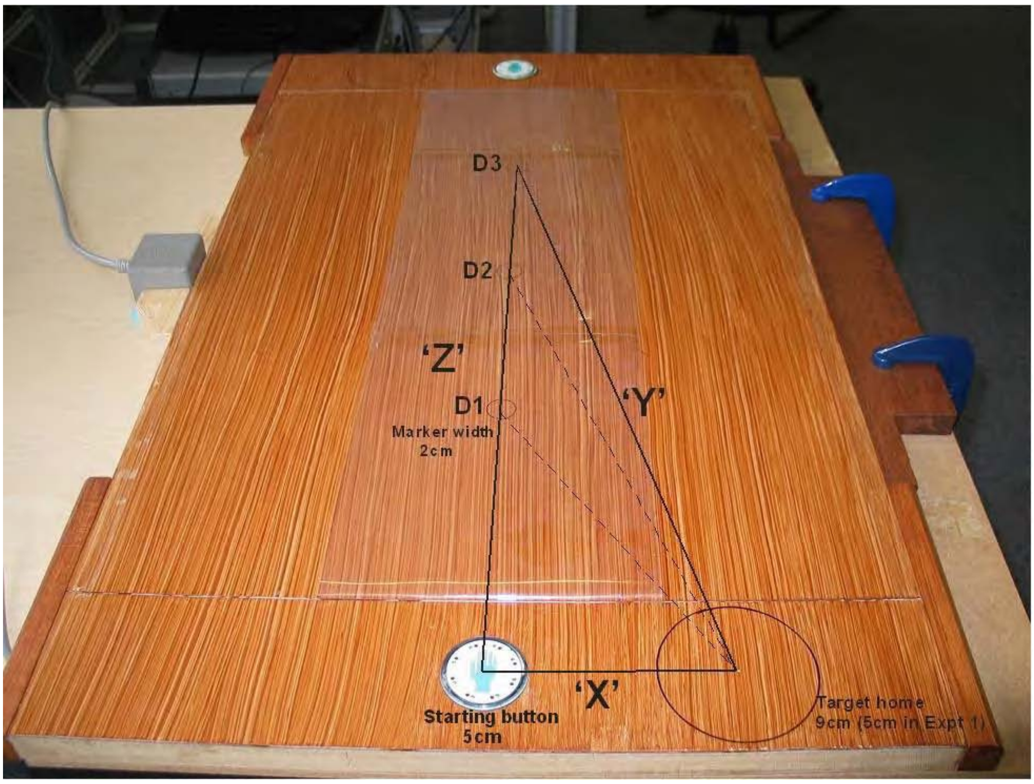
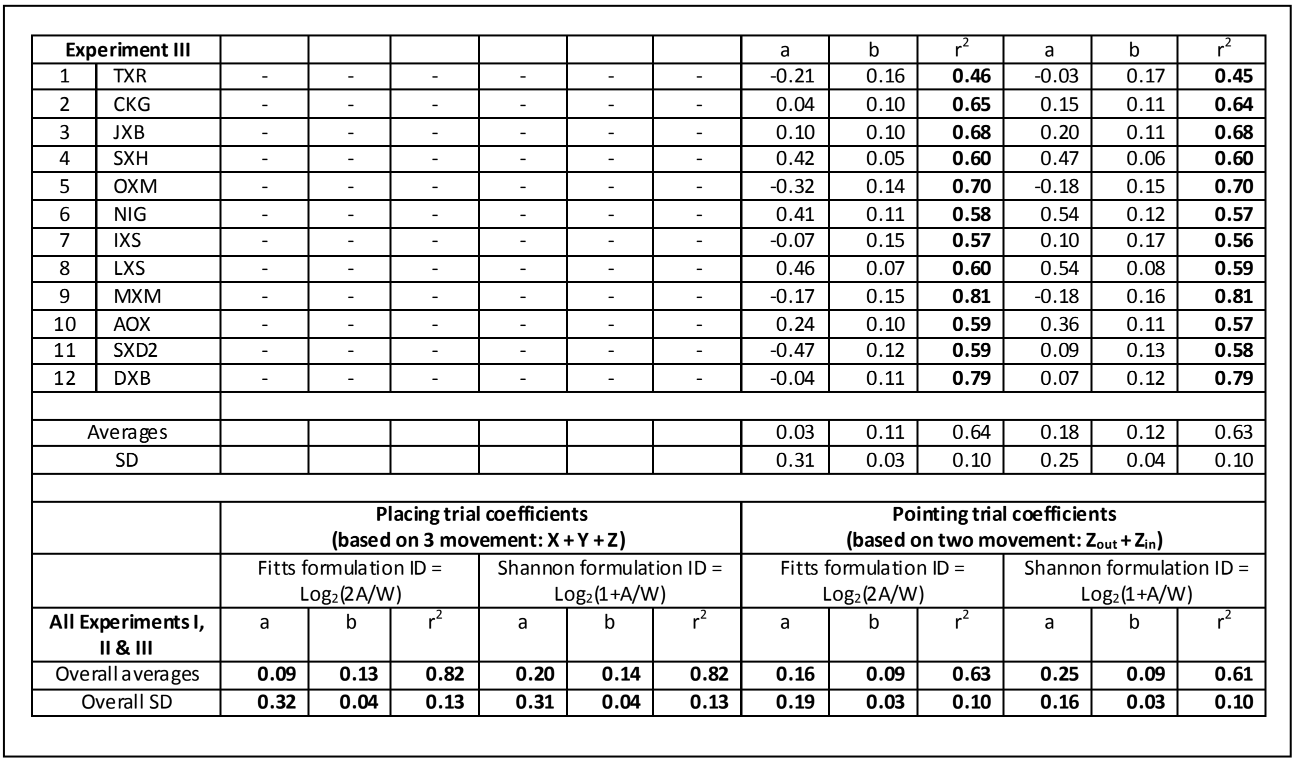


Table 4.3 Y-intercept (a) and slope (b) coefficients for each participant taken from the linear regression of average MT versus the sum of the IDs across all relevant submovements. Calculated separately for placing and pointing trials.

Table 4.3		**Placing trial coefficients (based on 3 movement: X + Y + Z)**						**Pointing trial coefficients (based on two movement: Z_{out} + Z_{in})**					
	Participant ID	Fitts formulation ID = Log$_2$(2A/W)			Shannon formulation ID = Log$_2$(1+A/W)			Fitts formulation ID = Log$_2$(2A/W)			Shannon formulation ID = Log$_2$(1+A/W)		
Experiment I		a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
1	AXM	0.34	0.12	**0.88**	0.44	0.13	**0.89**	0.20	0.09	**0.75**	0.29	0.10	**0.74**
2	IMS	0.23	0.13	**0.76**	0.34	0.14	**0.76**	0.37	0.06	**0.69**	0.43	0.06	**0.67**
3	MXB	0.16	0.12	**0.89**	0.27	0.13	**0.89**	0.35	0.07	**0.55**	0.42	0.07	**0.53**
4	MON	0.92	0.06	**0.40**	0.97	0.07	**0.41**	0.46	0.06	**0.58**	0.52	0.07	**0.57**
5	KXB	0.65	0.06	**0.52**	0.70	0.07	**0.53**	0.20	0.08	**0.82**	0.28	0.08	**0.80**
6	VJC	0.31	0.09	**0.74**	0.39	0.10	**0.74**	0.27	0.05	**0.50**	0.32	0.05	**0.48**
7	IXF	0.57	0.10	**0.83**	0.65	0.11	**0.83**	-0.02	0.12	**0.39**	0.11	0.13	**0.38**
8	RXG	0.19	0.13	**0.82**	0.30	0.14	**0.83**	0.31	0.08	**0.67**	0.39	0.09	**0.66**
9	NLM	0.20	0.11	**0.56**	0.30	0.12	**0.55**	0.31	0.05	**0.57**	0.37	0.06	**0.54**
10	FLO	-0.01	0.16	**0.89**	0.12	0.17	**0.89**	0.10	0.10	**0.49**	0.20	0.10	**0.47**
11	YXY	0.19	0.09	**0.86**	0.27	0.10	**0.87**	0.29	0.05	**0.75**	0.34	0.06	**0.74**
12	RAR	0.05	0.11	**0.97**	0.15	0.12	**0.97**	0.16	0.07	**0.79**	0.23	0.07	**0.78**
13	HLG	-0.35	0.16	**0.89**	-0.21	0.18	**0.90**	0.01	0.09	**0.71**	0.10	0.10	**0.70**
14	AXP	-0.10	0.15	**0.74**	0.03	0.17	**0.75**	0.12	0.08	**0.65**	0.20	0.09	**0.64**
15	OXM	0.03	0.13	**0.83**	0.15	0.15	**0.84**	0.33	0.06	**0.68**	0.38	0.06	**0.66**
16	CXD	-0.07	0.17	**0.95**	0.08	0.19	**0.95**	0.29	0.09	**0.49**	0.38	0.09	**0.47**
Averages		0.21	0.12	**0.78**	0.31	0.13	**0.79**	0.23	0.07	**0.63**	0.31	0.08	**0.62**
SD		0.31	0.03	**0.16**	0.29	0.04	**0.16**	0.13	0.02	**0.12**	0.12	0.02	**0.13**
		Fitts formulation ID = Log$_2$(2A/W)			Shannon formulation ID = Log$_2$(1+A/W)			Fitts formulation ID = Log$_2$(2A/W)			Shannon formulation ID = Log$_2$(1+A/W)		
Experiment II		a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
1	SXS	-0.01	0.13	**0.89**	0.11	0.14	**0.88**	0.13	0.07	**0.54**	0.21	0.07	**0.52**
2	VXM	-0.11	0.17	**0.77**	0.06	0.19	**0.77**	0.08	0.10	**0.58**	0.19	0.11	**0.57**
3	CXT	0.14	0.10	**0.86**	0.24	0.11	**0.86**	0.04	0.08	**0.82**	0.13	0.09	**0.81**
4	GLI	-0.35	0.16	**1.00**	-0.19	0.17	**0.99**	0.05	0.09	**0.68**	0.15	0.09	**0.67**
5	TXM	-0.32	0.19	**0.95**	-0.14	0.21	**0.95**	0.15	0.10	**0.62**	0.26	0.10	**0.60**
6	VRP	0.52	0.06	**0.85**	0.59	0.07	**0.85**	0.24	0.06	**0.78**	0.31	0.07	**0.78**
7	EJE	-0.23	0.16	**0.96**	-0.07	0.17	**0.96**	0.15	0.08	**0.56**	0.24	0.09	**0.55**
8	HXC	0.26	0.11	**0.80**	0.37	0.12	**0.80**	0.39	0.07	**0.48**	0.47	0.07	**0.47**
9	STH	-0.26	0.17	**0.96**	-0.09	0.19	**0.96**	0.17	0.09	**0.63**	0.27	0.09	**0.62**
10	HXN	0.25	0.10	**0.91**	0.35	0.11	**0.91**	0.19	0.06	**0.64**	0.25	0.07	**0.62**
11	JPK	-0.18	0.13	**0.88**	-0.49	0.15	**0.88**	0.31	0.05	**0.56**	0.37	0.06	**0.55**
12	LXS	-0.49	0.19	**0.97**	-0.30	0.21	**0.97**	-0.09	0.12	**0.61**	0.04	0.13	**0.59**
13	IXC	0.54	0.10	**0.69**	0.64	0.11	**0.69**	0.36	0.07	**0.64**	0.44	0.08	**0.62**
14	SXW	-0.10	0.13	**0.76**	0.03	0.14	**0.75**	0.07	0.07	**0.60**	0.15	0.07	**0.59**
15	SWC	0.06	0.14	**0.85**	0.19	0.15	**0.85**	0.25	0.07	**0.57**	0.33	0.08	**0.56**
16	KXC	0.21	0.12	**0.77**	0.34	0.13	**0.76**	0.13	0.09	**0.65**	0.23	0.09	**0.63**
17	HJK	-0.27	0.16	**0.68**	-0.12	0.17	**0.69**	0.14	0.08	**0.48**	0.23	0.09	**0.47**
18	CXH	0.21	0.13	**0.85**	0.33	0.14	**0.86**	0.37	0.07	**0.58**	0.45	0.08	**0.57**
19	LXB	0.02	0.12	**0.89**	0.13	0.13	**0.89**	0.02	0.09	**0.71**	0.11	0.09	**0.70**
20	SXD	0.66	0.06	**0.60**	0.71	0.06	**0.60**	0.16	0.06	**0.77**	0.23	0.07	**0.75**
21	RXW	-0.09	0.15	**0.95**	0.05	0.16	**0.96**	0.17	0.09	**0.59**	0.27	0.09	**0.58**
22	IAC	-0.42	0.19	**0.78**	-0.24	0.20	**0.78**	0.23	0.09	**0.50**	0.32	0.09	**0.49**
23	BXW	0.19	0.08	**0.69**	0.26	0.09	**0.70**	0.23	0.05	**0.63**	0.28	0.05	**0.61**
24	SXC	0.17	0.09	**0.76**	0.26	0.10	**0.77**	0.16	0.06	**0.60**	0.22	0.06	**0.60**
Averages		0.02	0.13	**0.83**	0.13	0.14	**0.84**	0.17	0.08	**0.62**	0.26	0.08	**0.60**
SD		0.31	0.04	**0.11**	0.30	0.04	**0.11**	0.12	0.02	**0.09**	0.11	0.02	**0.09**
		Fitts formulation ID = Log$_2$(2A/W)			Shannon formulation ID = Log$_2$(1+A/W)			Fitts formulation ID = Log$_2$(2A/W)			Shannon formulation ID = Log$_2$(1+A/W)		



Experiment III								a	b	r^2	a	b	r^2
1	TXR	-	-	-	-	-	-	-0.21	0.16	**0.46**	-0.03	0.17	**0.45**
2	CKG	-	-	-	-	-	-	0.04	0.10	**0.65**	0.15	0.11	**0.64**
3	JXB	-	-	-	-	-	-	0.10	0.10	**0.68**	0.20	0.11	**0.68**
4	SXH	-	-	-	-	-	-	0.42	0.05	**0.60**	0.47	0.06	**0.60**
5	OXM	-	-	-	-	-	-	-0.32	0.14	**0.70**	-0.18	0.15	**0.70**
6	NIG	-	-	-	-	-	-	0.41	0.11	**0.58**	0.54	0.12	**0.57**
7	IXS	-	-	-	-	-	-	-0.07	0.15	**0.57**	0.10	0.17	**0.56**
8	LXS	-	-	-	-	-	-	0.46	0.07	**0.60**	0.54	0.08	**0.59**
9	MXM	-	-	-	-	-	-	-0.17	0.15	**0.81**	-0.18	0.16	**0.81**
10	AOX	-	-	-	-	-	-	0.24	0.10	**0.59**	0.36	0.11	**0.57**
11	SXD2	-	-	-	-	-	-	-0.47	0.12	**0.59**	0.09	0.13	**0.58**
12	DXB	-	-	-	-	-	-	-0.04	0.11	**0.79**	0.07	0.12	**0.79**
Averages								0.03	0.11	0.64	0.18	0.12	0.63
SD								0.31	0.03	0.10	0.25	0.04	0.10
		Placing trial coefficients (based on 3 movement: X + Y + Z)						**Pointing trial coefficients (based on two movement: Z_{out} + Z_{in})**					
		Fitts formulation ID = $Log_2(2A/W)$			Shannon formulation ID = $Log_2(1+A/W)$			Fitts formulation ID = $Log_2(2A/W)$			Shannon formulation ID = $Log_2(1+A/W)$		
All Experiments I, II & III		a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
Overall averages		**0.09**	**0.13**	**0.82**	**0.20**	**0.14**	**0.82**	**0.16**	**0.09**	**0.63**	**0.25**	**0.09**	**0.61**
Overall SD		**0.32**	**0.04**	**0.13**	**0.31**	**0.04**	**0.13**	**0.19**	**0.03**	**0.10**	**0.16**	**0.03**	**0.10**

4.5.3 Implicit width

Using the placing coefficients obtained from the regression of baseline data, it was now possible to examine placing during interpersonal trials and uncover what was here termed 'implicit width'. This implicit width is the width of the area the participant was supposedly aiming for when they performed their placement of the target on to the workspace under no guidance (i.e., markers absent). Average placing MTs for a given target size during the interpersonal trials for a particular participant were known, as was their average placement distance (D) for that target size. By also inputting the placing regression coefficients (Table 4.3) from the baseline data, it was possible to solve for implicit width.

Placing trials were absent in Experiment III, therefore, placing coefficients could not be calculated for these participants. In lieu, placing coefficients (a, b) averaged from all participants in both Experiments I and II were used as an estimate. Doing this yielded an overall average implicit width across all target sizes in Experiment I of 2.83 cm (*SD* = 1.54), 3.83 cm (*SD* = 1.17) in Experiment II and 2.03 cm (*SD* = 2.55) in Experiment III (Shannon formulation) (Table 4.4).

$$\mathrm{MT}_{\text{Fitts interpersonal placing}} = a + b \cdot \log_2\left(\frac{2\sqrt{D^2+X^2}}{implicit\ width}\right) + b \cdot \log_2\left(\frac{2D}{button\ width}\right)$$

$$\ldots implicit\ width = \frac{4D \cdot \sqrt{D^2+X^2}}{button\ width \cdot 2^{\frac{MT_{placing}-a}{b}}}$$

or

$$\mathrm{MT}_{\text{Shannon interpersonal placing}} = a + b \cdot \log_2\left(1 + \frac{\sqrt{D^2+X^2}}{implicit\ width}\right) + b \cdot \log_2\left(1 + \frac{D}{button\ width}\right)$$

$$\ldots implicit\ width = \frac{button\ width \cdot \sqrt{D^2+X^2} + D \cdot \sqrt{D^2+X^2}}{button\ width \cdot 2^{\frac{MT_{placing}-a}{b}}}$$

Table 4.4 Implicit widths for Experiments I, II & III calculated for each target size and averaged across all participants.

<table>
<tr><th>Table 4.4</th><th colspan="2">Experiment I</th><th colspan="2">Experiment II</th><th colspan="4">Experiment III*</th></tr>
<tr><th rowspan="3">Formula</th><th rowspan="3">Fitts formulation ID = Log₂(2A/W)</th><th rowspan="3">Shannon formulation ID = Log₂(1+A/W)</th><th rowspan="3">Fitts formulation ID = Log₂(2A/W)</th><th rowspan="3">Shannon formulation ID = Log₂(1+A/W)</th><th colspan="2">Fitts formulation ID = Log₂(2A/W)</th><th colspan="2">Shannon formulation ID = Log₂(1+A/W)</th></tr>
<tr><th>a</th><th>b</th><th>a</th><th>b</th></tr>
<tr><th>0.09</th><th>0.13</th><th>0.20</th><th>0.14</th></tr>
<tr><td colspan="9">Target 1 (0.9cm)</td></tr>
<tr><td>MEAN</td><td>2.80</td><td>2.75</td><td>4.41</td><td>4.18</td><td colspan="2">2.70</td><td colspan="2">2.45</td></tr>
<tr><td>SD</td><td>1.60</td><td>1.52</td><td>2.80</td><td>1.71</td><td colspan="2">3.28</td><td colspan="2">2.95</td></tr>
<tr><td colspan="9">Target 2 (1.1 cm)</td></tr>
<tr><td>MEAN</td><td>3.08</td><td>3.02</td><td>4.75</td><td>3.21</td><td colspan="2">1.99</td><td colspan="2">1.79</td></tr>
<tr><td>SD</td><td>1.90</td><td>1.80</td><td>2.87</td><td>1.41</td><td colspan="2">2.64</td><td colspan="2">2.29</td></tr>
<tr><td colspan="9">Target 3 (2.0 cm)</td></tr>
<tr><td>MEAN</td><td>3.08</td><td>3.03</td><td>4.72</td><td>3.70</td><td colspan="2">2.04</td><td colspan="2">1.84</td></tr>
<tr><td>SD</td><td>1.69</td><td>1.60</td><td>3.40</td><td>0.90</td><td colspan="2">2.63</td><td colspan="2">2.28</td></tr>
<tr><td colspan="9">Target 4 (4.0 cm)</td></tr>
<tr><td>MEAN</td><td>2.63</td><td>2.60</td><td>4.44</td><td>3.73</td><td colspan="2">2.17</td><td colspan="2">1.95</td></tr>
<tr><td>SD</td><td>1.52</td><td>1.44</td><td>2.74</td><td>0.88</td><td colspan="2">2.93</td><td colspan="2">2.55</td></tr>
<tr><td colspan="9">Target 5 (6.0 cm)</td></tr>
<tr><td>MEAN</td><td>2.74</td><td>2.71</td><td>4.73</td><td>4.32</td><td colspan="2">2.32</td><td colspan="2">2.09</td></tr>
<tr><td>SD</td><td>1.39</td><td>1.34</td><td>3.23</td><td>0.96</td><td colspan="2">3.08</td><td colspan="2">2.70</td></tr>
<tr><td colspan="9">Average (averaged across all target sizes)</td></tr>
<tr><td>Overall</td><td>2.87</td><td>2.83</td><td>4.61</td><td>3.83</td><td colspan="2">2.25</td><td colspan="2">2.03</td></tr>
<tr><td colspan="9">SD (averaged across all target sizes)</td></tr>
<tr><td>Overall</td><td>1.62</td><td>1.54</td><td>3.01</td><td>1.17</td><td colspan="2">2.91</td><td colspan="2">2.55</td></tr>
<tr><td colspan="9">*As placing trials were absent in Experiment III, placing coefficients (a & b) averaged from all participants in both Experiments I & II were used instead.</td></tr>
</table>

4.5.4 Optimal placing

Using the regression coefficients in Table 4.3, a method was devised to establish the optimum placing distance based on a model in which participants should aim to minimize the joint trial time, where a trial begins with the onset of placer's movement and ends with the offset of pointer's movement. A mathematical model was used to calculate the optimal distance for placement of a target of a given size by iterating through all possible displacements and calculating the shortest possible MT, in accordance with the task instructions to minimize overall trial length. Total trial time (MT total) was assumed to correspond to the sum of the MTs of the placer and of the pointer (although in Experiment I this may not have been true as pointers could decide to begin their movement prior to the placer's return). In equation form the model can be summarized as:

$$Using\ Shannon\ formulation \ldots$$

$$\mathrm{MT}_{\mathrm{placer}}(i) = a_{placer} + b_{placer} \cdot \log_2\left(1 + \frac{\sqrt{X^2 + D(i)^2}}{average\ implicit\ width\ of\ placer}\right) + b_{placer} \cdot \log_2\left(1 + \frac{Z}{button\ width}\right)$$

$$\mathrm{MT}_{\mathrm{pointer}}(i) = a_{pointer} + b_{pointer} \cdot \log_2\left(1 + \frac{total\ length - D(i)}{target\ width}\right) + b_{pointer} \cdot \log_2\left(1 + \frac{D}{button\ width}\right)$$

$$MT_{total}(i) = MT_{placer}(i) + MT_{pointer}(i)$$

where a and b are the relevant coefficients of placer or pointer previously taken from Table 4.3, total length is the distance between placer and pointer buttons, average implicit width is the value calculated by averaging the implicit width values obtained for each of the different target sizes in a given participant acting as target placer (Table 4.5), and i is the value that iterates through D (i.e. the displacement distance between the placer button and target) using a specified interval. For Experiment III, just as for the implicit width calculation, the overall placing coefficients averaged across Experiments I and II were used.

Here the model iterated in increments of 0.5 cm through all possible amplitudes (D) from the minimum to the maximum placement distance which for Experiment I was between 14.2 and 54.2 cm and for Experiment II and III was between 9 cm and 72 cm. If a participant's arm reach fell below 72 cm, the maximum was set at their reach limit.

For Experiment I, using the relevant coefficients the optimal placing distance was found to be the minimum position irrespective of target size for all but three participants (Table 4.6). Of these three participants, the model suggested maximum placement was optimal. However, for one participant optimal placement for the four smallest targets was found to be the maximum position whilst the minimum placement position was optimal in the case of the largest Target 5. Additionally, these three participants were each paired with a partner for whom the minimum placing position had always been optimal.

For Experiment II, 16 participants should have opted for minimum placement whilst the remaining eight participants should have opted for maximum placement, regardless of target size (Table 4.6). In each of these eight cases where the maximum placement was optimal, these participants were paired with a partner whose optimal placement was the minimum placement position.

For Experiment III, in light of there being no placing trials, overall averaged regression coefficients for placing across both Experiments I and II were used. Irrespective of target size, maximum placement position was optimal for eight participants and minimum placement position was optimal for three participants (Table 4.6). For one participant, however, optimal placing for the smallest four targets was at maximum placement whilst for the largest Target 5, minimum placement emerged as optimal. This last participant was paired with another participant whose optimal strategy was always maximum placement. In the case of the three participants for whom the minimum placement position was optimal, they had each been paired with a partner whose optimal strategy was always maximum placement.

Table 4.5 Implicit widths for each participant averaged across all target sizes.

Table 4.5

Participant	**Experiment I**		**Experiment II**		**Experiment III**	
1	AXM	2.94	SXS	4.29	TXR	2.33
2	IMS	1.40	VXM	6.14	CKG	2.78
3	MXB	4.60	CXT	3.93	JXB	1.93
4	MON	2.70	GLI	4.70	SXH	1.12
5	KXB	0.66	TXM	2.91	OXM	8.64
6	VJC	3.29	VRP	2.14	NIG	0.16
7	IXF	1.35	EJE	2.20	IXS	0.13
8	RXG	5.35	HXC	4.21	LXS	0.62
9	NLM	3.89	STH	5.32	MXM	1.69
10	FLO	1.26	HXN	1.94	AOX	1.04
11	YXY	2.39	JPK	0.60	SXD2	1.09
12	RAR	2.53	LXS	4.92	DXB	2.54
13	HLG	1.71	IXC	15.32		
14	AXP	3.03	SXW	3.69		
15	OXM	2.79	SWC	11.13		
16	CXD	5.30	KXC	2.09		
17			HJK	6.49		
18			CXH	3.09		
19			LXB	1.77		
20			SXD	3.12		
21			RXW	2.52		
22			IAC	5.89		
23			BXW	4.12		
24			SXC	1.78		
	Calculated using Shannon formulation					

Table 4.6 Optimal placing distances derived from a model aimed at minimizing interpersonal trial time corresponding to the sum of placer and pointer MTs.

Experiment I		Target 1		Target 2		Target 3		Target 4		Target 5	
Max = 54.2 cm **Min = 14.2 cm** PPT ID		Model	Data (cm)	Model	Data (cm)	Model	Data (cm)	Model	Data (cm)	Model	Data (cm)
1	AXM	MIN	34.56	MIN	33.63	MIN	34.79	MIN	33.61	MIN	35.06
2	AXP	MIN	37.09	MIN	36.72	MIN	36.25	MIN	35.32	MIN	35.88
3	CXD	MIN	46.29	MIN	45.42	MIN	45.02	MIN	39.26	MIN	38.35
4	FLO	MIN	31.31	MIN	33.06	MIN	31.17	MIN	30.67	MIN	31.78
5	HLG	MIN	44.22	MIN	44.25	MIN	44.52	MIN	43.4	MIN	43.24
6	IXF	MIN	40.07	MIN	39.43	MIN	39.52	MIN	39.78	MIN	39.43
7	MON	MIN	39.21	MIN	37.97	MIN	37.83	MIN	38.53	MIN	38.6
8	MXB	MIN	45.03	MIN	45.93	MIN	45.42	MIN	45.42	MIN	45.73
9	NLM	MIN	38.16	MIN	38.06	MIN	37.89	MIN	37.79	MIN	37.59
10	OXM	MIN	35.37	MIN	40.47	MIN	39.03	MIN	34.08	MIN	35.18
11	RAR	MIN	36.51	MIN	36.61	MIN	36.28	MIN	35.99	MIN	35.89
12	RXG	MIN	44.22	MIN	44.17	MIN	44.13	MIN	42.6	MIN	44.41
13	VJC	MIN	37.66	MIN	38.13	MIN	38.72	MIN	37.93	MIN	38.01
14	YXY†	MAX	38.47	MAX	38.71	MAX	37.6	MAX	37.84	**MIN**	37.82
15	IMS	MAX	31.07	MAX	30.82	MAX	31.12	MAX	30.83	MAX	31.48
16	KXB	MAX	35.46	MAX	36.59	MAX	35.12	MAX	35.92	MAX	35.87
Experiment II											
Max = 72.0 cm **Min = 9.0 cm** PPT ID		Model	Data (cm)	Mode	Data (cm)	Model	Data (cm)	Model	Data (cm)	Model	Data (cm)
1	CXH	MIN	54.33	MIN	54.25	MIN	54	MIN	54.07	MIN	53.64
2	EJE	MIN	50.77	MIN	51.2	MIN	50.78	MIN	51.34	MIN	50.76
3	HJK	MIN	49.79	MIN	49.69	MIN	48.07	MIN	50.71	MIN	48.33
4	HXC	MIN	45.93	MIN	44.91	MIN	46.44	MIN	44.58	MIN	45.95
5	IAC	MIN	57.74	MIN	57.62	MIN	53.5	MIN	55.22	MIN	54.75
6	JPK	MIN	59.55	MIN	59.38	MIN	59.09	MIN	59.63	MIN	59.12
7	KXC	MIN	43.84	MIN	43.41	MIN	42.4	MIN	42.57	MIN	43.15
8	LXB	MIN	47.45	MIN	46.3	MIN	46.19	MIN	46.44	MIN	46.13
9	LXS	MIN	51.00	MIN	50.58	MIN	51.13	MIN	50.78	MIN	50.69
10	RXW	MIN	60.99	MIN	61.03	MIN	59.88	MIN	59.06	MIN	59.78
11	STH	MIN	46.94	MIN	44.38	MIN	45.67	MIN	46.37	MIN	45.38
12	SWC	MIN	62.07	MIN	61.46	MIN	61.75	MIN	61.19	MIN	61.64
13	SXC	MIN	65.22	MIN	62.48	MIN	55.71	MIN	54.4	MIN	49.17
14	SXW	MIN	35.11	MIN	43.45	MIN	43.04	MIN	42.14	MIN	38.62
15	TXM	MIN	57.08	MIN	59.41	MIN	57.62	MIN	59.15	MIN	58.14
16	VXM	MIN	52.69	MIN	51.7	MIN	53.06	MIN	54.56	MIN	52.9
17	BXW*	MAX	46.13	MAX	43.62	MAX	48.29	MAX	43.11	MAX	39.56
18	CXT	MAX	47.05	MAX	47.53	MAX	47.67	MAX	47.44	MAX	48.02
19	GLI	MAX	44.51	MAX	44.3	MAX	44.66	MAX	45.51	MAX	44.53
20	HXN	MAX	51.35	MAX	51.28	MAX	51.42	MAX	49.92	MAX	51.7
21	IXC*	MAX	48.88	MAX	48.83	MAX	48.09	MAX	48.82	MAX	48.47
22	SXD	MAX	47.28	MAX	46.74	MAX	46.75	MAX	46.12	MAX	45.65
23	SXS	MAX	43.13	MAX	42.38	MAX	42.4	MAX	44.15	MAX	44.12
24	VRP	MAX	48.89	MAX	49.35	MAX	49.09	MAX	49.4	MAX	49.09
Experiment III											
Max = 72.0 cm **Min = 9.0 cm** PPT ID		Model	Data (cm)	Model	Data (cm)	Model	Data (cm)	Model	Data (cm)	Model	Data (cm)
1	IXS	MIN	66.54	MIN	66.79	MIN	65.56	MIN	66.87	MIN	66.54
2	AOX	MIN	60.57	MIN	58.28	MIN	57.92	MIN	52.07	MIN	46.75

3	CKG	MIN	60.43	MIN	59.94	MIN	59.95	MIN	62.13	MIN	62.75
4	JXB*†	MAX	59.01	MAX	59.43	MAX	59.33	MAX	58.56	**MIN**	60.4
5	MXM*	MAX	67.65	MAX	69.15	MAX	67.89	MAX	67.92	MAX	67.88
6	TXR*	MAX	34.5	MAX	31.05	MAX	37.41	MAX	36.52	MAX	38.71
7	NIG	MAX	67.03	MAX	67.52	MAX	67.09	MAX	67.9	MAX	67.42
8	DXB	MAX	57.81	MAX	55.36	MAX	48.29	MAX	29.91	MAX	22.85
9	OXM	MAX	61.13	MAX	62.17	MAX	61.48	MAX	61	MAX	62.39
10	LXS	MAX	58.66	MAX	54.69	MAX	53.51	MAX	54.23	MAX	53.61
11	SXD2	MAX	64.38	MAX	61.93	MAX	59.07	MAX	55.21	MAX	41.62
12	SXH	MAX	66.78	MAX	66.39	MAX	65.73	MAX	67.11	MAX	66.82

***Reach limit of that participant †Changes across target size**

Calculated using Shannon formulation

4.6 Discussion

This chapter examined how participants' partitioned performances when working together to efficiently execute an aiming task which required one player to place the target down in order for the other player to hit it. The results indicated that interpersonal behaviour violated the optimal placing distances as suggested by Fitts' Law. In general, however, baseline (intrapersonal) performance conformed well.

4.6.1 Baseline data

In Experiments I and II, baseline trials indicated that placement trials took on average longer to execute than pointing trials. (In Experiment III only pointing trials were recorded, thus no comparison of trial type was possible.) This can be readily explained as pointing trials required that participants first reach to grasp the base of the target located some distance over to the right of their button before then placing the target down over the correct marker and returning back to their starting button. These additional movement requirements demanded a lengthier total movement distance which, combined with the added intricacy of stably transporting a weighted object over a given distance (absent in pointing trials), was likely responsible for the longer MTs observed for placing trials.

All three baseline experiments also unearthed that on average MTs made to the closest marker were significantly shorter in time than those made to the intermediate marker, which in turn were significantly shorter than those made to the furthest marker. This was true for both trial types and is in line with Fitts' Law, which predicts that as the distance of a target increases, so too does the MT required in order to successfully reach that target (Fitts, 1954). It is worth mentioning that although a structured array (i.e., placeholders marking possible target locations) was used, that data showed linear increases in MTs with larger distances. This goes against reports by Adam et al. (2006), who found that MTs to the most distant target were shorter than MTs to the second-to-last target when placeholders were present—although the comparison between this current task and theirs may not be a fair one, as firstly, they employed a larger range of placeholder positions and secondly, the onset of target appearance was unpredictable in their task.

Target size was also revealed to play a decisive role in shaping MTs across all experiments. Across all baseline experiments, in every comparison that yielded a significant difference across two targets, it was the larger of these two targets that resulted in shorter average MTs, with a difference of a few hundredths of a second in most cases. This result also corroborates Fitts' Law, which predicts that hitting smaller targets will require longer MTs because the index of difficulty increases as the target width decreases.

Experiment I and II also unveiled little divergence in average MTs during placement trials (with one exception between Targets 1 and 4 in Experiment II, although importantly target weights were not equal at that time). Conversely, for pointing trials, MTs were shorter for larger compared to smaller targets, providing strong support for Fitts (1954) findings. This disparity across trial types is understandable when one remembers that during placement trials, participants always transported the target by its base, which was of identical width across all target sizes. During pointing trials, however, participants had to adjust their MTs in accordance which the index of difficulty specified by the target width, which varied.

Furthermore, in Experiment II the MT advantage for larger targets compared to smaller ones was especially pronounced as target distance increased. This hinted at a floor effect in MTs for larger targets as they approach peripersonal space. In other words, it may simply not have been possible to distinguish between targets on the basis of MT at very close distances because what limited the action (especially in tasks such as this one which entailed large body movements) is no longer the target width but was instead other factors which impact on MT, but that cannot be readily modified such as muscle activity transmission times or other biomechanical constraints.

Overall, results from the baseline data provide strong evidence in support of the basic tenets of Fitts' Law, reconfirming the notion that target distance and width play a role in controlling MT by modulating the index of difficulty of the task. Furthermore there is evidence to suggest that these effects are particularly noticeable when acting on targets placed further out.

Of note, however, is the poor linear fit of the MT data to the pointing target index of difficulty across all experiments, which represented a clear violation of Fitts' Law. However, these overall MTs were driven by the return aspect of the movement (i.e., the amplitude term in the Fitts equation), which dominated the MT results and obscured the influence of the width component in the Fitts equation. An attempt to partition out some of the variation from the return component was done for pointing trials in Experiments I and II. Doing so revealed a stronger linear fit (i.e., MT increased as index of difficulty increased), which implied that the amplitude term was indeed contributing strongly to the total MT in the data. This represented a limitation of the task, as MT was measured for the combined movement (reach and return) as opposed to each component separately (i.e., discretely).

4.6.2 Interpersonal placement data

Across all three experiments during interpersonal trials where participants were free to choose a location to place the target at for their partner, the placement distances obtained were not found to vary with respect to target size. This went against the initial hypothesis that participants might place smaller targets closer to their task partner than larger targets, so as to reduce the index of difficulty this partner would experience when hitting the target. In essence, what had been predicted was a linear trend between placing distance and target size, which was not confirmed. Instead, results indicated that participants performed similarly across all target sizes, although a trend towards higher placement distances for the smaller targets was evident in Experiments I and II. This was indicated by a tendency for negative slope coefficients (i.e., an inverse relationship) obtained from a regression of placing distance and target size.

The model, which predicted the optimal placing distance that ensured shortest MTs by utilizing the baseline data from each pairing of players, revealed that, in almost all cases, the optimal distance was either the maximum or minimum placing distance for all targets across all participants. There were only two participants for which the optimal placing distance changed from maximum to minimum dependent on the target size. In both cases, this change occurred so that for smallest target, maximum placement was preferable to the minimum placement, which had been the optimal placement for all the other larger targets. The actual average placement data for each participant with each target also showed that participants usually performed suboptimally, as generally there remained a considerable gap between the optimal placing distance suggested by the model and the actual distances seen in the data.

One possibility is that participants were simply placing at the most comfortable location based on some biomechanical factor of arm movement, perhaps to reduce effort or stretch of the arm. However, if this were the case, it is somewhat surprising that in Experiment I placements were an average of 38.16 cm, whilst for the other experiments placement distances were much farther (approximately 50 cm) despite there being sufficient space (54.2 cm) on the board in Experiment I to place further out at a distance more congruent with those found in the other experiments.

Another important potential factor at play could be the interpersonal nature of the task itself. This might have engaged participants in placement behaviour that took into account not only speed and accuracy as emphasized in the instructions, but also more subjective properties such as performing one's 'fair share' of the workload in the task. Notably, the average placements were usually greater than would be expected had placers simply aimed for a position on the board halfway between them and their task partner, which in the case of Experiment I would 34.2 cm and for the other experiments would be 40.5 cm. In fact the overall average placement distances were 38.16 cm (*SD* = 4.27), 50.30 cm (*SD* = 6.11) and 57.96 cm (*SD* = 10.92) in Experiments I through III, respectively, or 3.04 cm, 9.80 cm and 17.46 cm from the centre of the workspace. It therefore appears that placers were not merely attempting to perform the task so as to equally share the movement distance covered across the board with their task partner. Instead placers were willing to put in more than their 'fair share' of movement across the board. Perhaps, for instance, the role of the placer was deemed more dominant in the task as they initiated the interpersonal action and so they might have expected to take on more of the workload responsibility (although not so much as to be fully optimal which would be 'unfair'). Socio-economic psychological perspectives might speak to this last point. For instance, there is emerging evidence to support the idea that humans value fairness over efficiency (Hsu, Anen, & Quartz, 2008; Sanfey, 2007). Moreover, reciprocal altruism is seen as a key concept in cooperation human actions (Nowak & Sigmund, 1998; Rilling et al., 2002; Trivers, 1971).

At this stage it is unknown whether the results here simply represent evidence against an interpersonal adherence to Fitts' Law similar to that reported by Fine and Amazeen (2011) or whether the design of the task was such that the interpersonal goal to reduce overall MT was not strong enough to elicit such effects. Mottet et al. (2001) provided evidence that Fitts' Law is obeyed in multi-person interactions at least in a reciprocal aiming paradigm. They concluded that Fitts' Law has little to do with how many people are engaged in the task and instead suggest that the law is an abstract relationship that 'lives' in task space, that is, the (one-dimensional) space determined by the distance separating the pointer from the target.

Their task differed significantly from this current study, however, as in their design the two members of an interacting pair each independently controlled either the pointer or the target and, critically, these objects were permitted to be moved simultaneously with respect to each other. By contrast, in the current task placing and pointing were sequential. Furthermore these authors placed emphasis on the study of the chronometric and kinematic patterns of behaviour whilst the current study was more focused at looking at how motor strategy (placing behaviour) evolved as a consequence of shared task difficulty. Interestingly, Mottet et al. (2001) noted no effect of hand assignment on MTs, which suggested that participants were partitioning labour symmetrically (i.e. equally) as opposed to asymmetrically in their variant of a dynamic concurrent reciprocal aiming task. This was seen as evidence in favour of and an extension via interpersonal cooperative cases of, the bimanual synchronization tendency seen previously using a competitive two-handed within-persons aiming paradigm (Kelso et al., 1979). In support of bimanual synchronization but showing that Fitts' Law could be violated, Fine and Amazeen (2011) revealed, however, that when target difficulty was unequal across both hands/participants, participants violated Fitts' Law in favour of synchronization even when participants were not required to engage directly with each other. Therefore, the debate is still open as which conditions give rise to lawful behaviour and which do not.

Just why participants performed suboptimally in their placement behaviour in this present task is intriguing. If as suggested by Mottet et al. (2001), it is the distance between the target and the pointer (i.e. task space), which is key to Fitts' Law, then behaviour in the task should have favoured strictly symmetric placement behaviour. In fact, it was not found that placers displaced targets midway between themselves and their partner. Instead, placers here showed an asymmetric 'altruistic' pattern of behaviour by tending to place beyond the midpoint. This highlights the differences which may arise depending on the chronology of the actions required by the task, as different behaviour may emerge depending on whether interpersonal actions are performed concurrently or sequentially, the study of which would be worthy to pursue in future research.

Furthermore, had the present task been more explicit, for instance by telling participants about Fitts' Law ahead of performing the task, more 'optimal' behaviour as predicted by the model might have been seen. However, this manipulation would not be representative of natural action. Interpersonal *baseline* trials might have possibly allowed participants to more readily naturally observe the effect of index of difficulty on their task partner ahead of performance trials in which placement was at the discretion of the placer. Equally, providing feedback on combined MTs (MT placer + MT pointer) might also have made the goal to reduce trial time more salient. It is possible that the instructions to reduce MT in the task was not enforced as rigorously as it might have been. One change to the paradigm, for instance, could involve very specific trial times to effectively force participants to operate under very constrained time conditions. Under these extreme ends of task condition, it might be more likely that behaviour would adapt to fall in line with Fitts' Law in a more readily observable manner.

Strategic effects such as always placing at the same location regardless could also not be ruled out. A way to combat this might be to incentivize or force participants to alternate placements distance so that for example they could not place a target of a given size at the same location two times in a row. By constraining the action possibilities available to participants, behaviour might evolve so as to minimize trials time perhaps by maximizing closeness of smaller targets over larger ones, although of course there could be no guarantee of this. The concept of constraining placing width might provide a promising avenue for further research into Fitts' Law during interpersonal exchanges, by, for example, examining mathematically (i.e., tailored to each individual's performance coefficients) the critical implicit width at which different regimes (i.e., minimum versus maximum placing) should be chosen for small versus large targets.

The analysis to reveal implicit width itself was done in an attempt to extract novel understanding of the placer's actions. Although not directly addressing the core aims of the experiments to probe interpersonal adherence to Fitts' Law, it was considered potentially of interest to Fitts' Law research in the broader sense. The implicit width was the estimated width area that the participant was aiming for when placing the target on to the workspace. The computation of this measure assumed that the coefficients for movement during baseline trials were identical to those during interpersonal trials, thus enabling target area to be calculated during interpersonal placing. The results indicated an overall average implicit width across all target sizes in the approximate region of 2–4 cm, which was consistent with the size of the makers used in baseline trials as well as the grid squares in Experiments I and II. The average implicit size also fell within the range of target sizes (width averaged across all targets = 2.80 cm) utilized in the task. To current knowledge, this type of implicit width data is original and the results are presented here as preliminary findings only, as further research would be necessary to add weight to the results obtained here.

To summarize, the results were initially surprising in that no differences in target displacements were found across the target sizes during the interpersonal task, however, this finding was in line with the model that predicted no differences. Furthermore the actual interpersonal placement data acquired typically did not conform to the optimal strategy suggested by the model either. Nor did it represent symmetric partitioning of labour between task partners seen previously in an interpersonal Fitts task (Mottet et al., 2001). Instead, asymmetric behaviour persisted whereby placers characteristically took on more of the workload of the task, but not to the degree of being fully optimal, suggesting a possible trade-off between efficiency and equity (Hsu et al., 2008; Sanfey, 2007).

Since it is known how seemingly adept humans are at interacting with each other in performing actions with shared goals, it is hard to envision that Fitts' Law should not operate between-persons as well as within-persons. However, the data fail to confirm this claim and the experiments reported here demonstrate, if nothing else, that the conditions that mediate interpersonal behavior in relation to Fitts' Law are not obvious and may be modulated by multiple experimental design factors such as the salience of the shared goal, the explicitness of task instructions, the temporal order of action responses required and the measures used as an indicator of adherence. It seems reasonable to conclude that whilst the baseline records showed cohesive evidence in support of longer MTs for higher indices of difficulty (although the target width component was heavily overridden by the amplitude component especially at closer distances), when applied to between-person interactions the evidence is far from unequivocal and becomes less straightforward to capture using one simplistic measure.

The fundamental difficulties in researching interpersonal action, that is, action brought about by the coupling of two or more independent entities working together under a shared goal, should not be underestimated. As yet the two published studies investigating Fitts' Law under between-persons conditions show inconsistent results (Fine & Amazeen, 2011; Mottet et al., 2001). Just as in individual behaviour, there is undoubtedly still much scope for future research in the area of Fitts' Law. Specifically, uncovering disassociations with regards to which conditions give rise to or violate lawful Fitts behavior would be of particular significance in understanding successful interpersonal actions.

CHAPTER FIVE

EFFICIENCY OR EQUITY IN DISTRIBUTING OPTIMAL CONTROL: INTRAPERSONAL AND INTERPERSONAL PERFORMANCE DIFFERENCES DURING A NOVEL REACH-TO-TARGET TASK

5.1 Introduction

This chapter describes two experiments designed to test how participants differed in the motor strategy they adopted during their performance in a novel reach-to-target task, where the movement of a single onscreen cursor towards one of four targets was either jointly controlled by two vBOT manipulanda operated bimanually by one participant (Experiment I, Intrapersonal) or independently operated by two participants, each in control of one vBOT handle (Experiment II, Interpersonal). Specifically of interest was how participants would choose to partition the share of movement towards a given target depending on the difficulty level experienced by each hand or player.

5.1.1 Motor Tasks and Game Theory

Interpersonal actions are both commonplace and varied in form, even when only two agents are considered. For example, key to ensemble dance performance is cooperation, as dancers frequently must attend to and complement the actions of one another. By comparison, the actions undertaken by two boxers are highly competitive in nature, with each opponent aiming to catch the other by surprise so as to land the decisive blow. In both cases, the shared sensorimotor control of the 'umbrella' task, whether cooperative or competitive, implicates that the actions of one agent impacts on the motor choices or decisions of the other co-agent.

The study of decision-making is concerned with how individuals process multiple options in order to settle on the optimal solution (Sanfey, 2007). Critically, many life decisions are made in the heat of social interactions, which are equally co-dependent on the associated decisions of others. One approach to the study of social interactions comes from research in the area of game theory, which is a computational method for examining how individuals make decisions using principles rooted in economic theory (Sanfey, 2007).

Recently, Braun, Ortega and Wolpert (2009) have applied game theory to the study of continuous *motor* coordination decisions in two sensorimotor tasks which tapped into reciprocal exchange between players The first of these tasks was akin to the prisoner's dilemma game (PDG) studied extensively in game theory and the second task was a novel rope-pulling paradigm.

In the PDG (see Sally, 1995) two players must independently choose whether or not to cooperate with each other. If both cooperate to claim innocence, both are sentenced to three years of prison, whereas if both defect claiming the other to be guilty both will be imprisoned for a hefty seven years. The other alternative is that one player defects whilst the other cooperates, leaving the defector freed and the cooperative player sentenced to the maximum 10 years. The penalties are the game's payout function. Similarly, in the rope game (Braun et al., 2009), players manoeuvre separate ropes both attached to a single weight. Players are paid according to how far they pull the weight in a given direction, with one player rewarded in one direction and the other rewarded by movement in the orthogonal plane. The globally optimal cooperative strategy is for both players to pull the weight equally along a diagonal; however, the optimal strategy for the individual would be to try to gain at the cost of the other player by pulling the weight further along their rewarded direction. In both of these games, the Nash equilibrium solution (Nash, 1950), or the best solution for one player given all the possible strategies of other players, is to defect. This is because the maximum punishment (or minimum payout) is always averted, with the player also having nothing to gain from a change in only their strategy. In effect, players minimize their maximum effort. In contrast, the globally optimal strategy for both players would be to always to cooperate.

In game theory, the decisions in such tasks are usually discrete as there exists only a fixed number of possible outcomes (i.e. payouts), making the monitoring of the co-agent during the decision-making process unnecessary. Braun et al. (2009), however, ensured continuous coupling of players during their variant of the PDG. To do this, they linearly interpolated the payout between cooperation and defection of both players so that payout could now vary continuously between previously discrete response categories, dependent on the actions of both agents right up until the very last moments of the trial. Payout in their version was represented by movement effort. Minimizing energy cost was seen as the implicit goal, as being energy cost efficient is thought to be instrumental in human motor control (Todorov & Jordan, 2002).

In the PDG task described by Braun et al. (2009), two participants (or one participant playing bimanually) controlled, via robot handles, the movement of cursors towards targets presented to each player individually, but simultaneously. The lateral position of the cursor on the target bar represented the relative level of cooperation or defection, with each end representing the absolute category. Motion of each robot was resisted by spring forces whose strength was dependent on the action (cooperation or defection) of both players. The game's payout function was thus the spring constant applied to each robot. However, participants were not explicitly aware of the payout function (as is usually the case in game theory) and instead could only learn the optimal strategy through in-task experience. Braun et al. (2009) discovered that players executing the task bimanually opted for cooperative solutions, while interpersonal actions were characterized by a preference for Nash defection solutions. Thus, different optimal strategies emerged for intrapersonal versus interpersonal conditions, presumably because in the interpersonal condition feedback about the other player's behaviour was solely restricted to force payout.

In their rope-pulling paradigm (Braun et al., 2009), the control variable was now two dimensional and was dependent on the vector sum of the positional movements of both handles relative to their starting positions. Cooperative action required movement along the diagonal, whilst the Nash solution required each handle to be moved only in the rewarded direction, which differed across players. Forces were hence not dependent on the other player; however, the position of the weight was, such that interpersonal coordination was necessary to reach the target, as disregarding the actions of the other player was no longer viable. As with the PDG, during bimanual conditions cooperative solutions were preferred, as evidenced by pulling directions clustered at 45° for both arms. During the interpersonal task pulling, however, directions tended on average to be the Nash equilibrium solution of 0° and 90° for the two players. Therefore, when faced with unpredictable interpersonal situations, participants tend to minimize their maximum effort by biasing play to their own self-advantage.

More recently, Braun, Ortega and Wolpert (2011) have also studied dyad co-adaptation during coordination games with multiple Nash equilibria, which required participants to coordinate their actions *together* so as to attain the optimal Nash solutions. In the PDG, there had been only one Nash solution meaning that participants could independently select their optimal strategy. This was now no longer possible, as the optimal solution required coordination of equilibrium selection. Participants played motor variants of four coordination games which either required pure coordination (both players choosing the same strategy) or miscoordination (both players choosing opposing strategies) to attain the optimal solution. An example of pure coordination is 'choosing sides', in which two people walking towards each other in a hallway must both opt to step to their right (or both to their left) so as to pass each without incident. By contrast, in the miscoordination 'chicken' game, two vehicles are on a collision course with one another and the optimum solution is for one player to swerve and the other to stay put. This outcome is better than both being called chicken for both swerving or sure death for both staying put. There are four possible solutions for these games, two of which are coordinated and two of which are miscoordinated: (1) both players cooperate, (2) both players defect, (3) Player 1 cooperates whilst Player 2 defects and (4) Player 1 defects whilst Player 2 cooperates. Whilst the possible solutions are known, the process which mediates equilibrium selection is unknown. Accordingly Braun et al. (2011) investigated the idea that within-trial adaptation could offer a mechanism for how coordination solutions are selected.

The design was similar to the PDG (Braun et al., 2009) and the final decision (i.e., the lateral endpoint) of both players on each trial was plotted against each other in a plane. This enabled the relative level of cooperation to be classified into four quadrants, each of which represented one of the four possible outcomes. In all games except the chicken game (which was the only game to require miscoordination), coordination solutions were significantly more likely than miscoordination. In the chicken game, however, although the worst case scenario of both players choosing to 'stay' was significantly less probable, the evolutionary stable strategy to both swerve, which represented a mixed Nash equilibrium, was as likely as the optimal pure Nash miscoordinated solution.

Across all tasks it therefore seemed that when players were unable to select the optimal strategy independently, they still found it possible to actively explore the payoff landscape within-trial, so that dyad performance became increasingly correlated through co-adaptation. Thus even when payoff landscapes were changed for every trial and when players were unaware of the consequences of their actions on the other player (i.e. the forces given to the other player were not accessible), successful coordination was still able to emerge naturally without the need to necessarily predict the actions of the other player. The authors suggest, however, that had their design involved a payout landscape that was constant over trials, thereby facilitating learning, predictive internal models for dyad interaction may too have been forged. The authors conclude that future work should explore the notion that evolutionary stable strategies are better placed than Nash equilibria to model and interpret interpersonal motor coordination. It is worth mentioning also, that participants were instructed to minimize restrictive forces in these tasks (Braun et al., 2009; Braun et al., 2011) and there were no explicit instructions to cooperate. Thus information about the task partner's behaviour was limited to the forces and/or information in the visual display. Overall, Braun and colleagues have demonstrated how game theory can provide a method to the study of between-persons motor control.

Relatedly, haptic coupling has been implicated elsewhere in interpersonal coordination (Reed et al., 2006). Reed et al. (2006) examined individual and dyad performance using a two-handled crank apparatus which rotated a circular disk. The task was to move a marking on this disk to the target location projected on the disk. Participants performed alone (unimanually) or with a partner (unseen but known to be present throughout) who simultaneously viewed equivalent marker and targets. Crank handles were mechanically linked such that both participants completed the task at identical times. Force recordings revealed that participants exerted greater force during dyad compared to individual trials. This finding also ties in with previous research undertaken by Shergill, Bays, Frith and Wolpert (2003). These authors demonstrated that when participants were required to match the force level previously applied to them by another participant, force production in dyads escalated in tit-for-tat fashion, in contrast to the considerable attenuation shown for matching self-generated forces (Shergill et al., 2003).

Furthermore, Reed et al. (2006) noted that increased force did not simply represent the faster member of the pair pulling along the slower member, as average dyad completion times were notably shorter than those of the fastest member of the dyad when performing alone. This suggested an emergent strategy for improved task performance that was only accessible to the dyad condition. As interaction between dyad members was limited to mechanical coupling, the authors speculated that haptic information is one mechanism for developing a cooperative interpersonal coordination strategy.

5.1.2 Interpersonal Action: Through the Eyes of Dynamical Systems Theory and Motor Control

Continuous interpersonal motor coordination has also been studied from a dynamical systems perspective (Kelso, 1995; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990; Schmidt & Turvey, 1994). The dynamical systems approach views motor behaviour as a dynamical process of self-organization between an agent and its past, present and future environment, explicable using mathematical principles (Marsh, Johnston, Richardson, & Schmidt, 2009; Schmidt, 2007). The majority of studies have involved rhythmic tasks in which dyads synchronize with one another the swinging of leg movements or hand-held pendulums in either an in-phase or anti-phase mode (Schmidt et al., 1998; Schmidt et al., 1990; Schmidt & Turvey, 1994). Despite no physical coupling between agents, the visual information available to each agent regarding the performance of their task partner was sufficient to elicit successful interpersonal coordination which mimicked the pattern of behaviour observed during within-persons coordination. Namely, as oscillation frequency increased, coordination stability during anti-phase modes decreased and participants frequently transitioned from anti-phase to in-phase modes of synchrony, but not the reverse.

In optimal control theory, in contrast to dynamical systems theory, motor control is understood as the consequence of a central nervous system (CNS) developmentally or evolutionarily tuned to optimize some index of performance, such as reducing jerkiness or energy cost (Nelson, 1983; Schaal, Mohajerian, & Ijspeert, 2007; Todorov & Jordan, 2002). To achieve this, the sensorimotor consequences (feedback signals) of an action are compared against the predicted outcome of the original motor command, allowing discrepancies influencing the task goal to be corrected in subsequent behaviour. Miall and Wolpert (1996) propose that forward models operating at the level of the CNS receive a copy of the motor command, termed the efference copy, which is then combined with information concerning the current body state and external environment. The end result of this process allows a prediction of the motor consequences of an action to be formed. Wolpert, Doya and Kawato (2003) suggest that the computational mechanisms underlying individual behaviour (specifically the use of internal forward models) may be extended and applied to model between-person motor actions, through a predictive process that estimates the state of others, as well as one's own state.

Thus both dynamical systems and optimal control approaches model behaviour mathematically, and lately an attempt has been made to derive a unifying framework for both perspectives, which it is argued may in fact be complementary (see Schaal et al., 2007). As Braun et al. (2011) note, the Nash equilibria concept investigated by their work has meaning as both a point attractor state in a dynamical system and also as a pertinent behavioural parameter such as energy cost or task accuracy in an optimal control model.

5.1.3 Reaching Towards Targets

Of relevance to this current reach-to-target study, when reaching towards a target, arm movements typically take on straight smooth trajectories with bell-shaped velocity profiles

(Abend, Bizzi, & Morasso; 1982, Sejnowski, 1998). Just why reaching behaviour is so similar across individuals has been a core interest of computational motor control, as it implies that individuals are optimizing their movements. Kinematic models have suggested that individuals execute movements so as to optimize the smoothness of their movements by minimizing jerk, that is, the rate of change in acceleration (Flash & Hogan, 1985). Others have advocated more dynamical models in which the change in torque is minimized (Uno, Kawato, & Suzuki, 1989).

More recently, a leading computational theory in human motor control has been put forth, which suggests that behaviour is actually optimized in favour of minimizing endpoint error (Harris & Wolpert, 1998). This 'minimum-variance' model is founded on the physiological hypothesis that motor commands are subject to signal-dependent noise from the firing of motor neurons (Harris & Wolpert, 1998). Thus, as the size of the neural control signal increases, for example when computing a high-speed movement, so too does the noise of the motor command carried to the muscles. The net result is more variable motor output. Put more simply, the variability in the muscle output increases with the strength of the motor command (Sejnowski, 1998). Moreover, this framework unifies both the kinematic and dynamical explanations of smooth movements (Kawato, 1999). As Kawato (1999) explains, endpoint variance represents a kinematic variable which is modulated by the strength of the motor command, which is itself determined by the dynamical properties of the body's motor system and environment. The minimum-variance model has the advantage of not requiring that the CNS computes highly derived signals (e.g. jerk) in order to estimate the cost of a movement as, instead, these costs are accessible directly (Harris & Wolpert, 1998). Thus, optimal movements are naturally smooth not because smoothness is maximized, but rather, because sudden jerky movement changes would require large changes in the neural signals, which would introduce noise in to the movement, undoubtedly representing a suboptimal solution.

Fitts' Law (Fitts, 1954) predicts that endpoint precision becomes harder to achieve as the movement amplitude to a target becomes lengthened and as the target width decreases in size. The minimum-variance model, which postulates that endpoint precision is maximized over movement efficiency has been found to reliably predict the speed-accuracy trade-off immortalized by Fitts' Law. Taken together, these last points raise the question of how participants would trade-off task efficiency with endpoint precision when performing under the bimanual (intrapersonal) and interpersonal task conditions examined in this current work.

5.1.4 Equity and Efficiency

In addition to the concerns related to regulating movements efficiently, there are also far more 'social' concerns raised by interpersonal motor control, namely, that of distributive justice, defined as the trade-off between equity and efficiency or more generally, the process by which people allocate benefits and burdens in a just or moral manner (Hsu, Anen, & Quartz, 2008). For example, is it better to feed five starving children well or feed ten starving children meagerly? Utilitarian justice (Harsanyi, 1976) approaches to such dilemmas promote the view that efficiency or utility should win out irrespective of equity concerns and thus, in the example it would make more sense to well-feed the minority. In stark opposition, deontological approaches to similar situations advocate that equity (i.e., feed all ten children) is preferable to efficiency, as efficiency can actually be perceived as immoral when it contravenes a right, rule or duty (Hsu et al., 2008).

Indeed, there is emerging evidence to support the idea that humans value fairness over efficiency, even when efficiency is in their self-interest (Hsu et al., 2008; Sanfey, 2007). This dominant trend towards mutual cooperation in humans appears to be grounded in the concept of reciprocal altruism (Rilling et al., 2002; Trivers, 1971). Reciprocal altruism whether direct or indirect in nature may be the mechanism by which, over the course of interactions, the reputation or 'image' of players becomes established or 'scored' (Nowak & Sigmund, 1998). In this sense, reciprocity serves a cornerstone function in cooperative action.

Hsu and colleagues (2008) investigated the neural correlates associated with equity and efficiency in a distributive justice paradigm requiring participant to pass judgments on how to allocate meals to hungry children whilst undergoing functional magnetic resonance imaging. The putamen, a well acknowledged 'reward' region in the brain (Schultz, 2000) was found to respond to measures of efficiency, whilst the insula, thought to underpin emotion regulation (Sanfey, Rilling, Aronson, Nystrom, & Cohen, 2003), appeared to code inequity. From their work, Hsu et al. (2008) concluded that differences in strategies occurred due to participants placing different weights upon inequities rather than efficiency, providing support for the deontological position, but with an emphasis in emotional rather than rational processing.

In summary, whilst task instructions may emphasize efficiency, which itself might simply be a by-product of minimizing endpoint error, at least in the motor domain (Harris & Wolpert, 1998), it would be imprudent to ignore social equity concerns, such as sharing task responsibility, when *interpersonal* action is at study. Additionally, understanding how different perspectives attempt to explain the similarities as well as reconcile any differences in intrapersonal and interpersonal coordination is a valuable pursuit in motor control research and was the focus of this current study.

A novel reach-to-target task was employed, where the movement of a single onscreen cursor towards one of four targets was jointly controlled by two vBOT manipulanda operated bimanually by one participant (Experiment I) or interpersonally by two participants, each in control of one vBOT handle (Experiment II). For each participant/hand, randomly directed lateral force perturbations acted on the vBOT handle making movement toward two of the targets difficult; movement in the other two directions was unperturbed. The two participants/hands experienced one shared 'difficult' direction and one shared 'easy' direction; the other two directions were difficult for one participant/hand and easy for the other.

It was predicted that participants would deduce, based on their own prior isolated experience of the task and the information available to them in the display, which directions were easy or difficult for their interpersonal actions. In Experiment I, this entailed separate unimanual performance of each hand prior to bimanual performance using both hands simultaneously. On the other hand, in Experiment II, participants executed the task alone on one hand before interpersonal performance with another participant. It was anticipated that participants would predict over the course of trials when it was advantageous (in terms of accuracy and speed) for them to contribute more heavily to the task, such as when movement to one target was easier for them than compared to their partner (or easier for one hand compared to the other).

It was hypothesized that for efficient cooperative actions, the participant/hand in the 'easy' condition should generate more of the shared cursor movement when their partner/other hand was is in a 'difficult' condition, as this would reduce exposure to forces and so minimize the difficulty involved in achieving the goal. Behaviour was probed using catch trials in which force perturbations were absent during normally 'difficult' target conditions for a given hand/participant.

5.2 Method

5.2.1 Participants

5.2.1.1 Experiment one (Intrapersonal)

Seventeen healthy right-handed (self-reported) students (11 female) from the University of Birmingham with a mean age of 22.06 years (SD = 3.25 years) were recruited.

5.2.1.2 Experiment two (Interpersonal)

Eighteen healthy right-handed (self-reported) students (10 female) from the University of Birmingham with a mean age of 25.10 years (SD = 3.12 years) took part as nine dyad pairs.

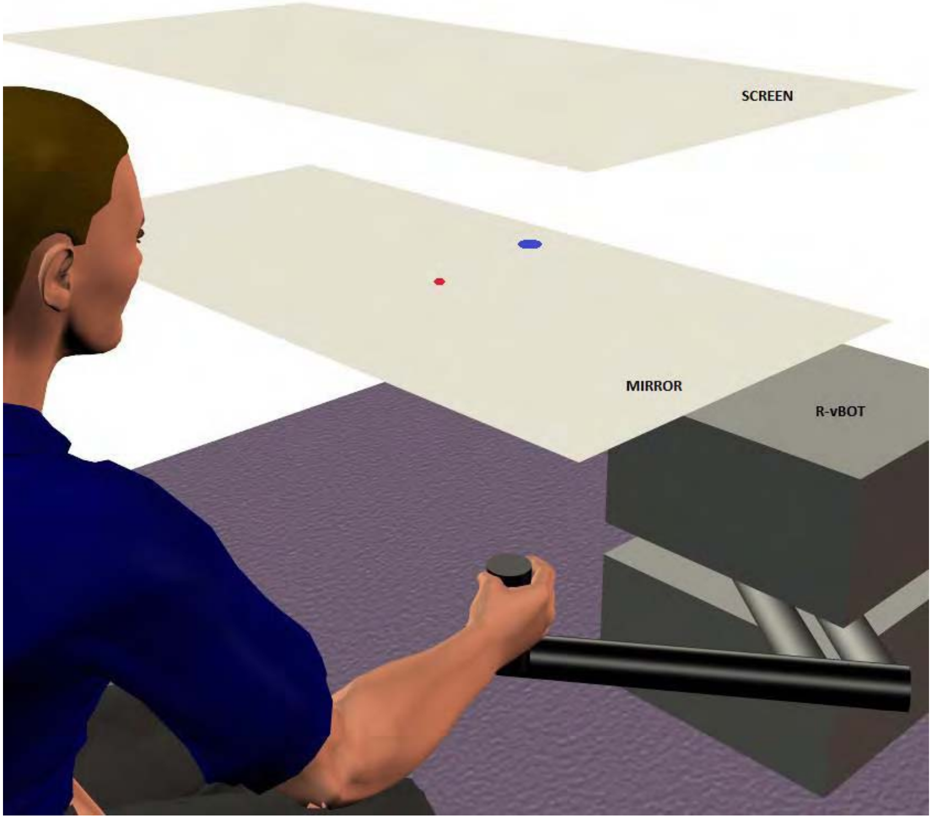
All participants had normal or corrected-to-normal vision and no other known sensory or motor abnormalities. Participants were naïve to the purpose of the study for which they were compensated with a choice of research credits or £4 cash. Prior to participation, each volunteer provided informed consent.

5.2.2 Apparatus and Materials

Each participant interacted with one (Experiment II) or both (Experiment I) of two identical and symmetrically positioned force-generating robotic manipulanda that constrain movements to the horizontal plane (vBOTs, Jackson & Miall, 2008). Participants used their instructed hand(s) to move the vBOT handle(s) which in turn controlled the movement of a red circular cursor (radius 0.5 cm) displayed on a 30-inch (54.3 H × 68.8 W cm) flat screen monitor. This monitor was positioned above a mirror which sat perpendicular to the participant at roughly chest height and which enabled the participant to view the virtual images of the stimuli (cursor and targets) in the mirror as though in the same plane of movement as the actual vBOT handles. Both monitor and mirror were situated exactly midway between the left (L-vBOT) and right (R-vBOT) robots (Figure 5.1). On each trial the onscreen cursor would always begin at the centre of the screen, laterally translated from the location of the hand, which was displaced 35 cm laterally to the left for L-vBOT or to the right for R-vBOT. The cursor was thus equidistant from the starting positions of both robots allowing both manipulanda to be operated concurrently. For Experiment II, dark cloth was draped around the edges of the mirror set-up so that participants were prevented from seeing their own hand in the individual task and their partner's hand in the interpersonal task.

Participants sat on a tall stool in front of the mirror, centrally (Experiment I) or side by side (Experiment II). For comfort they rested their feet on a foot rest and seat height was adjustable to ensure a good view of the mirror set-up. The monitor was connected to a nearby computer which displayed the stimuli onscreen. Stimuli display (both cursor and targets) was reversed in the X-direction so that rightward movement of the vBOT would produce leftward movement of the cursor which when viewed as a reflection in the mirror would appear to be moving in the 'correct' rightward direction. The same principle applied for leftward movements and also for 'left' and 'right' target positions. It was not necessary for the Y-direction to be reversed as movements of the cursor in this axis were accurately preserved in the mirror image. The same computer also controlled the robots and saved the data obtained from their sensors. These sensors recorded the position and velocity of the vBOT handles at a 1000 Hz sampling rate and the output forces applied to the robots during perturbation trials were updated at this same rate.

Figure 5.1 vBOT set-up depicting the unimanual (Experiment I) and individual (Experiment II) task.



5.2.3 Design and Procedure

5.2.3.1 Experiment I (Intrapersonal)

This experiment comprised three parts. The first two parts were performed unimanually, first with one hand on one vBOT and then with the other hand on the other vBOT, with order counterbalanced across participants. In the final part, participants completed the task bimanually using both vBOTs. R-vBOT was always operated with the right hand and L-vBOT was operated with the left hand.

5.2.3.1.1 Unimanual Task

Participants sat with the centre of the mirror at their body midline, equidistant from both robots so that for later bimanual trials it was in the optimal position for both hands. Participants were randomly assigned to begin with either the vBOT manipulandum located to the left (L-vBOT) or right (R-vBOT) of the screen. They would later perform the same task with the other hand and other vBOT (144 trials per vBOT). Prior to beginning the task they were given a brief demonstration on how to operate the vBOT handle before performing five practice trials, which were not recorded. Following this exposure, the actual experiment began. At the beginning of each trial, the robot passively moved the manipulandum into the starting position which was approximately 35 cm offset to the left (for L-vBOT) or to the right (for R-vBOT) of the centre of the screen. As soon as the vBOT was in place, the red cursor would appear in the screen centre and a circular blue target (1 cm radius) would appear onscreen at one of four possible locations 10 cm away from the cursor's starting position. The four position possibilities were: top (0°), bottom (180°), left (90°) and right (270°). Each target position appeared 36 times in randomized order, over the course of the task. Immediately upon being positioned at the correct starting location, a buzzer would generate a series of beeps (two 100 ms in length and a third longer beep which lasted 700 ms, each separated by 200 ms from each other), indicating to the participant that they should prepare to make their movement towards the target on the third beep (not before) and also attempt to end this movement before the third beep had finished. Movement recordings began at the onset of the third beep and lasted 4 s.

The participant's task was to move the cursor on to a given target both as quickly and as accurately as possible and to keep the cursor there until the end of the trial, where the vBOT would then return the handle back into the correct starting position. The instructions also indicated to participants that they might notice some targets would be 'harder to reach' than others and that learning which target positions were most difficult might help them in completing the task more efficiently. For each vBOT, randomly directed lateral force perturbations were applied to the vBOT handle making movement towards two of the targets difficult. Movements in the other two directions were unperturbed and hence 'easy'. For the L-vBOT, the perturbed difficult directions were always for top and left target positions whilst for the R-vBOT the difficult directions were always for top and right target positions. Hence, both hands experienced one shared 'difficult' direction (up) and one shared 'easy' direction (down); the other two directions (left, right) were difficult for one hand and easy for the other. Participants were never explicitly told which directions were difficult for them. In addition to the perturbed trials, there were also a small number of catch trials (12) where no perturbation was applied in the otherwise normally difficult direction. For example, a right target in which no forces were applied to the R-vBOT would represent a catch trial, as this target position was perturbed more often than not (i.e. two thirds of the time) for R-vBOT. Performance during catch trials was used as the key measure to probe motor strategy. In total each unimanual task involved 144 trials lasting approximately 14 minutes for each vBOT.

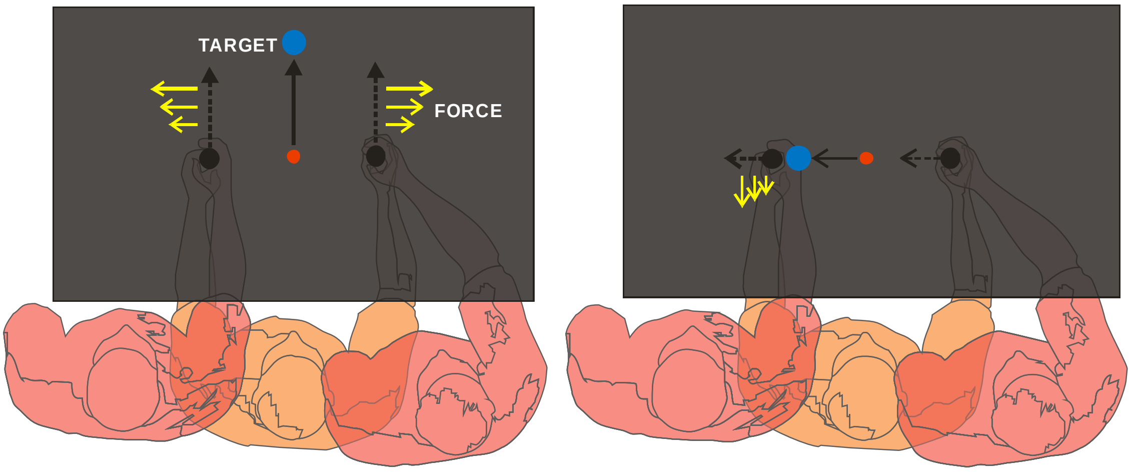
5.2.3.1.2 Individual Bimanual Task

After completing both unimanual parts of the experiment, participants moved on to complete the bimanual task using both vBOTs (Figure 5.2, orange player). Task instructions and the presentation of targets, cursor and beeps were identical to those in the unimanual task. The only difference was that now both vBOTs jointly controlled the movement of the (single) onscreen cursor. At the beginning of each trial both vBOT handles were simultaneously moved into their respective starting positions on either side of the cursor. Crucially, participants were informed that the cursor now represented the average position of both vBOTs and thus how far the cursor moved and where it moved to was now dependent on the movements of both vBOTs. Therefore, if both hands contributed equally to the task, each would have to move their vBOT handle by 10 cm in the direction of the target to produce a 10 cm movement of the cursor towards the target. Likewise, if one hand was to do all the work whilst the other remained stationary, the moving hand would have to produce a 20 cm movement of the vBOT handle in the direction of the target to produce a 10 cm movement of the cursor towards the target.

The target-dependent perturbations applied to a given vBOT handle were identical across unimanual and bimanual conditions so both hands experienced 'top' targets as 'difficult', 'bottom' targets as 'easy' and the other two directions (left and right) were difficult for one hand and easy for the other, as in the unimanual case. The aim was that through unimanual exposure to the task participants might learn that when using both hands, it would be more advantageous (in terms of accuracy and speed) to contribute more heavily to the task with a particular hand when that hand was in an 'easy' as opposed to 'difficult' condition. The bimanual task also lasted 144 trials.

For both experiments across unimanual, intrapersonal and interpersonal conditions there was a position dependent field constant of -0.72 Newtons/cm for forces. This field constant was multiplied against vBOT position meaning that the further the displacement of a movement in the direction of a difficult target position, the stronger the forces became in pushing the participant off in a direction lateral to the intended movement. To reach the target under these conditions, these forces must be resisted. Right targets were always difficult for the right vBOT and left targets were always difficult for the left vBOT. Of the 144 trials in each separate experiment, there were an equal number of 36 trials for each target position. For the two difficult target positions, perturbations were applied randomly to the left (12 trials) or right (12 trials) of movement. There were also 12 catch trials under both sets of normally difficult conditions where perturbations were now absent. These perturbation and catch trials were distributed randomly throughout the course of the 144 trials. For the easy target positions no vBOT-generated perturbations were ever experienced. Each trial recording lasted 4 seconds.

Figure 5.2 Bimanual (orange) and interpersonal (red) trial examples. [All arrows for illustration purposes only.]



Depicted above is a matched trial to the TOP target, difficult for both hands/players. In this example a rightward perturbation is applied to R-vBOT and a leftward perturbation is applied to L-vBOT.

Depicted above is a mismatched trial to the LEFT target, difficult only for the left hand/player. In this example a leftward perturbation is applied to L-vBOT whilst R-vBOT is unperturbed.

5.2.3.2 Experiment II

This experiment comprised three parts. The first two parts were performed by each participant individually. Each participant from a pair was assigned to perform unimanually on of the two vBOTs (the other participant would later operate the other vBOT) as described previously, except now they only ever acted on one vBOT handle and always with their dominant right hand. The final part was completed by both participants together, with each person operating their designated vBOT handle to jointly control the movement of a single cursor.

5.2.3.2.1 Individual task

Participants were divided into nine gender-matched pairs, each tested separately. Participants from a pair arrived in the lab at the same time, at which point one of the dyad was randomly assigned to perform the individual part of the task first on either L-vBOT or R-vBOT, whilst the remaining member of the pair would later perform the individual task on the other vBOT (order counterbalanced across participants). When one member was performing the unimanual section of the study, they were kept out of view of their task partner.

Two stools were set up by the apparatus, one directly in front of each vBOT. Participants were seated at the stool in front of the vBOT they were controlling and were hence always slightly offset from the centre of the mirror (to allow participants to sit side by side in later interpersonal trials), although all screen content remained fully visible to them. All other experimental details were identical to those of the Experiment I except that now different participants (interpersonal) rather than different hands (intrapersonal) experienced one shared 'difficult' direction (top) and one shared 'easy' direction (bottom); the other two directions were difficult for one participant and easy for the other.

5.2.3.2.2 Interpersonal Task

After both participants from a pair had completed the individual task, they were then both returned to the same vBOT they had previously used to begin the interpersonal task

The interpersonal task was identical to the bimanual task described in Experiment I except that rather than one participant operating both vBOTs together to control the movement of a single onscreen cursor, now the two participants from each pair worked jointly to complete the task, each operating one vBOT handle each with their dominant hand. Participants were given the same information about how the onscreen cursor now represented the average position of both vBOT handles and thus the position to where the cursor moved was dependent on the movements of both parties. Participants were instructed that they should 'work together' with the 'joint aim' of moving the cursor to the target as quickly and as accurately as possible. Target difficulty experienced by each participant was the same as in their individual task. It was predicted that participants would predict when it was more advantageous (in terms of accuracy and speed) for them to contribute more heavily to the task. For instance, they might generate more of the shared cursor movement when they were in an 'easy' condition whilst their partner was in a 'difficult' condition.

Participants were never explicitly told which directions were difficult for them nor were they told which directions were difficult for their task partner. Any judgments made regarding this could thus only be inferred from their individual and interpersonal performance. Furthermore during the interpersonal task participants wore noise-reduction headphones to block out the sound of the forces being ramped up during perturbation trials (although the beeps used in the task were still sufficiently audible through the headphones). The only information available to them about their task partner's movements was what they could observe in the display. Therefore participants could only infer the difficulty (i.e. perturbations) experienced by their task partner by what they observed within-trial onscreen.

5.3 Analyses

Using the recorded position and velocity data, the size of displacements in the direction of the target for each vBOT across trials performed either bimanually (Experiment I) or as part of a dyad (Experiment II) was explored across matched and mismatched trials. The unimanual (Experiment I)/individual (Experiment II) part of the task was not examined as it served only to familiarize participants with the relative movement difficulty for each target direction prior to performance in the later individual bimanual and interpersonal conditions. In matched trials, both vBOTs experienced a shared easy target direction (bottom), which was always unperturbed and a shared difficult target direction (top), which was perturbed on two thirds of trials, randomized for a given vBOT. In mismatched trials, the L-vBOT uniquely encountered perturbations to two thirds of trials in which movements were made to the left target whilst movements to the right target were always unperturbed. By contrast, the R-vBOT uniquely experienced perturbations on two thirds of trials in which movements were made to the right target whilst movements to the left target were always unperturbed.

Thus, the critical measure was performance during the one third of unperturbed trials (catch trials) in the otherwise usually difficult direction in both matched and mismatched conditions. To garner understanding of how labour was partitioned across the two hands or two participants, the final position of each vBOT at trial conclusion was obtained for all catch trials (12 trials for the top target and 12 trials for the vBOT-unique difficult target direction) and all trials that were always unperturbed for both vBOTs (36 trials for the bottom target and 36 for the vBOT-unique easy target direction). End position was calculated as displacement in the direction of a target relative to the starting position of each vBOT. Across both vBOTs, this totaled 3264 trials in the bimanual task and 1728 in the interpersonal task (Table 5.1).

Next, the average velocity during the last 100 ms of movement was averaged across all examined trials for a given target direction and vBOT. Trials whose velocity over this last 100 ms period was above two standard deviations of this average were excluded for being unstable. Such trials indicated that the participant was still engaged in above-average movement as the trial came to termination at 4000 ms, long after the third beep had ended (1500 ms into the trial). Across all participants, 5.73% and 5.67% of examined trials were excluded on this basis for the bimanual and interpersonal tasks respectively (see Table 5.1).

Subsequently, the movement distances for each of the remaining trials were averaged to give the mean distance travelled in a specific target direction. This process was done separately for both vBOTs. To estimate the relative contribution from each hand, the average displacement of the right (hand or Participant 1) and left (hand or Participant 2) vBOTs was compared using the following relative proportional measure:

$$Relative\ contribution\ of\ \ vBOTS\colon \frac{right\ vBOT - left\ vBOT}{right\ vBOT + left\ vBOT}$$

Values obtained using this measure could ranged from +1 (where R-vBOT contributed all movement) to -1 (where L-vBOT contributed all movement); a value of 0 signified both vBOTs contributed equally. R-vBOT and L-vBOT were either controlled bimanually (intrapersonal) or between participants (interpersonal).

Doing this yielded for each participant or participant pair a relative value which indicated which hand or participant contributed more to a given target direction (Table 5.2).

These values were used for the analysis of the relative displacement contributions across the different targets in both tasks.

Table 5.1: Breakdown of excluded trials

	Table 5.1 Excluded trials								
BIMANUAL TASK	LEFT HAND, L-vBOT				RIGHT HAND, R-vBOT				**TOTAL TRIALS**
TARGET:	TOP	RIGHT	BOTTOM	LEFT	TOP	RIGHT	BOTTOM	LEFT	
EXAMINED TRIALS, ALL PARTICIPANTS (N = 17)	12 × N = 204 CATCH TRIALS ONLY	36 × N = 612	36 × N = 612	12 × N = 204 CATCH TRIALS ONLY	12 × N = 204 CATCH TRIALS ONLY	12 × N = 204 CATCH TRIALS ONLY	36 × N = 612	36 ×N = 612	**3264**
EXCLUDED TRIALS, ALL PARTICIPANTS	17	36	30	15	15	15	32	27	**187**
PROPORTION EXCLUDED	8.33%	5.88%	4.90%	7.35%	7.35%	7.35%	5.23%	4.41%	**5.73%**
INTER-PERSONAL TASK	PARTICIPANT 1, L-vBOT				PARTICIPANT 2, R-vBOT				**TOTAL TRIALS**
TARGET:	TOP	RIGHT	BOTTOM	LEFT	TOP	RIGHT	BOTTOM	LEFT	
EXAMINED TRIALS (N = 18, 9 PARTICIPANTS PER vBOT)	12 × 9 = 108 CATCH TRIALS ONLY	36 × 9 = 324	36 × 9 = 324	12 × 9 = 108 CATCH TRIALS ONLY	12 × 9 = 108 CATCH TRIALS ONLY	12 × 9 = 108 CATCH TRIALS ONLY	36 × 9 = 324	36 × 9 = 324	**1728**
EXCLUDED TRIALS, ALL PARTICIPANTS ON GIVEN vBOT	6	20	17	4	5	9	19	18	**98** (47 L-vBOT; 51 R-v VBOT)
PROPORTION EXCLUDED	5.56%	6.17%	5.25%	3.70%	4.63%	8.33%	5.86%	5.56%	**5.67%** (5.44% L-vBOT; 5.90% R-vBOT)
NOTE: For each vBOT, movements towards two targets were difficult (top target for both vBOTs, left target for L-VBOT, right target for R-vBOT, all in blue); movement in the other two target directions were unperturbed (bottom target for both vBOTs, right target for L-VBOT, left target for R-vBOT).									

Table 5.2 Relative values obtained using a proportional measure of the relative contribution of each vBOT for each participant (Experiment I) or participant pair (Experiment II)

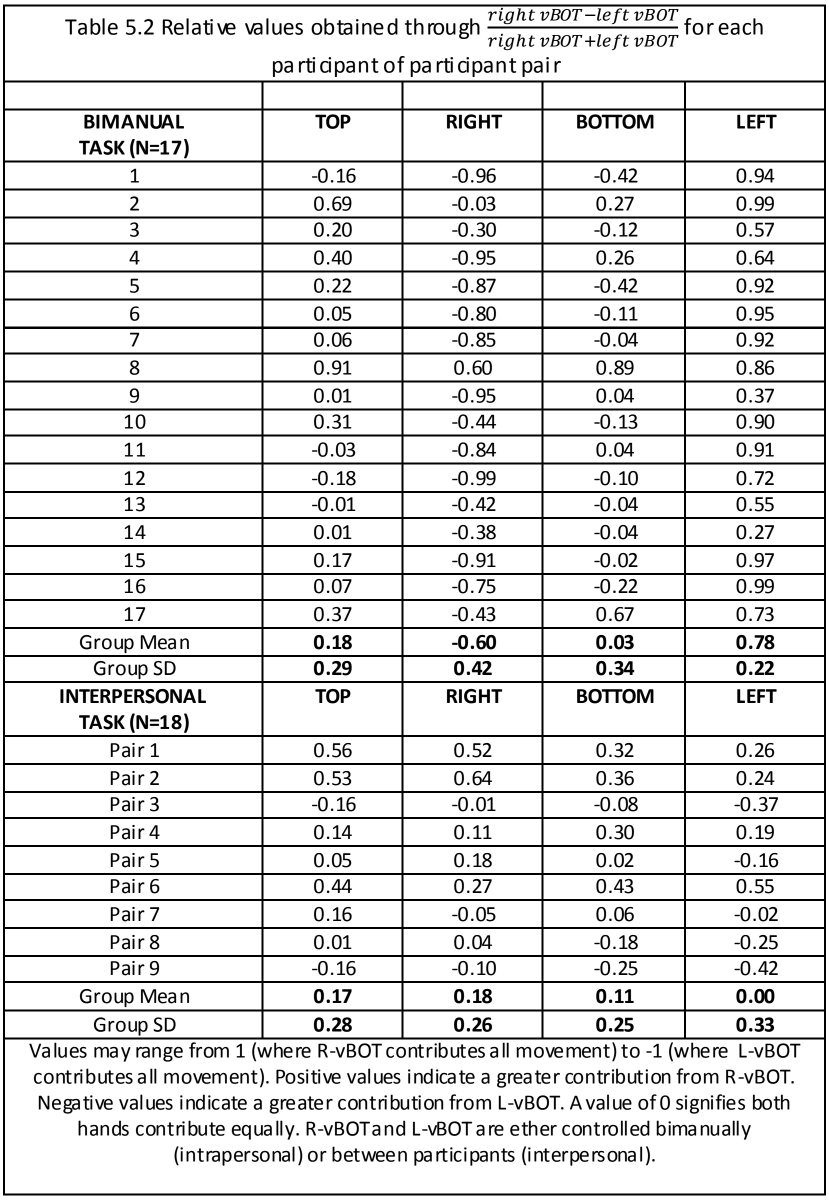


Table 5.2 Relative values obtained through $\frac{right\ vBOT - left\ vBOT}{right\ vBOT + left\ vBOT}$ for each participant of participant pair

BIMANUAL TASK (N=17)	**TOP**	**RIGHT**	**BOTTOM**	**LEFT**
1	-0.16	-0.96	-0.42	0.94
2	0.69	-0.03	0.27	0.99
3	0.20	-0.30	-0.12	0.57
4	0.40	-0.95	0.26	0.64
5	0.22	-0.87	-0.42	0.92
6	0.05	-0.80	-0.11	0.95
7	0.06	-0.85	-0.04	0.92
8	0.91	0.60	0.89	0.86
9	0.01	-0.95	0.04	0.37
10	0.31	-0.44	-0.13	0.90
11	-0.03	-0.84	0.04	0.91
12	-0.18	-0.99	-0.10	0.72
13	-0.01	-0.42	-0.04	0.55
14	0.01	-0.38	-0.04	0.27
15	0.17	-0.91	-0.02	0.97
16	0.07	-0.75	-0.22	0.99
17	0.37	-0.43	0.67	0.73
Group Mean	**0.18**	**-0.60**	**0.03**	**0.78**
Group SD	**0.29**	**0.42**	**0.34**	**0.22**
INTERPERSONAL TASK (N=18)	**TOP**	**RIGHT**	**BOTTOM**	**LEFT**
Pair 1	0.56	0.52	0.32	0.26
Pair 2	0.53	0.64	0.36	0.24
Pair 3	-0.16	-0.01	-0.08	-0.37
Pair 4	0.14	0.11	0.30	0.19
Pair 5	0.05	0.18	0.02	-0.16
Pair 6	0.44	0.27	0.43	0.55
Pair 7	0.16	-0.05	0.06	-0.02
Pair 8	0.01	0.04	-0.18	-0.25
Pair 9	-0.16	-0.10	-0.25	-0.42
Group Mean	**0.17**	**0.18**	**0.11**	**0.00**
Group SD	**0.28**	**0.26**	**0.25**	**0.33**

Values may range from 1 (where R-vBOT contributes all movement) to -1 (where L-vBOT contributes all movement). Positive values indicate a greater contribution from R-vBOT. Negative values indicate a greater contribution from L-vBOT. A value of 0 signifies both hands contribute equally. R-vBOT and L-vBOT are ether controlled bimanually (intrapersonal) or between participants (interpersonal).

5.4 Results

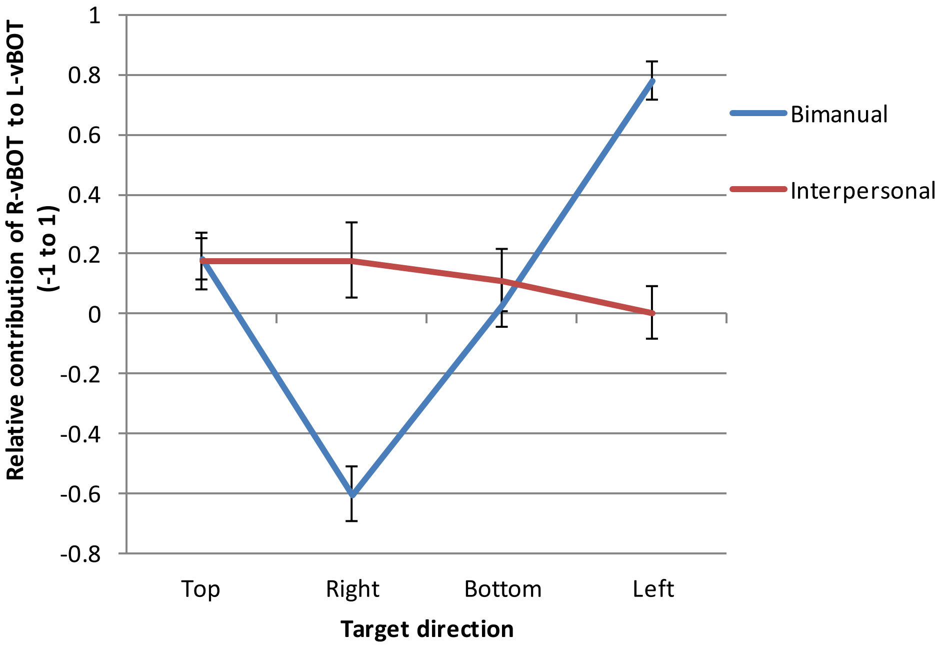
A mixed-design repeated measures ANOVA was conducted on the average relative displacement values (see section 5.3) with one between-participants variable (Task type: bimanual or interpersonal) and one within-participants variable (Target: top - difficult for both; bottom - easy for both; right - difficult for R-vBOT; left - difficult for L-vBOT). Task type was nonsignificant, $F(1, 24) = 0.37$, $p > .05$, $\eta_p^2 = .00$. Within-participants effects revealed a main effect of target, $F(1.95, 46.78) = 32.15$, $p < .001$, $\eta_p^2 = .57$. The interaction between target and task type was also significant, $F(3,72) = 51.76$, $p < .001$, $\eta_p^2 = .68$ (Figure 5.3). Simple effects analyses were carried out to interpret the nature of this interaction.

Significant target effects were only found in the bimanual condition, $F(3, 22) = 64.79$, $p < .001$, $\eta_p^2 = .90$. Here, the average relative contribution value for the top target was 0.18 (*SE* = 0.07), for bottom target was 0.03 (*SE* = 0.08), for the left target was 0.78 (*SE* = 0.06) and for the right target was -0.60 (*SE* = 0.10). In the interpersonal task, where no significant differences were noted ($p > .05$), the average relative contribution value for the top target was 0.17 (*SE* = 0.10), for bottom target was 0.11 (*SE* = 0.10), for the left target was 0.00 (*SE* = 0.09) and for the right target was 0.18 (*SE* = 0.13).

Bonferroni pairwise comparisons for the bimanual task revealed highly significant differences throughout all target comparisons ($p < .001$), with the exception of the comparison between the top and bottom target, whose significance was weaker ($p = 0.03$). Results from the bimanual task imply that participants opted to use their right hand much more than their left hand for left (easy for right, hard for left) targets (average relative values > 0) and their left hand much more than their right hand for right (easy for left, hard for right) targets (average relative values < 0). For bottom targets, participants opted to use both hands relatively equally (close to zero discrepancy across hands) whilst for top targets there was a slight, but significant, preference for using the right dominant hand.

Furthermore, significant task type effects were found only for right and left targets, $F(1,24) = 25.28$, $p < .001$, $\eta_p^2 = .51$ and $F(1,24) = 50.89$, $p < .001$, $\eta_p^2 = .68$, respectively. Bonferroni pairwise comparisons confirmed the differences of task type on right and left targets were highly significant, both $p < .001$. This indicated that whilst in the interpersonal task, movement towards left and right targets was shared relatively equally across participants, in the intrapersonal task the unperturbed hand took over more of the movement during conditions where it was easier for this hand to perform than the other.

Figure 5.3 The average relative contribution of the right R-vBOT compared to L-vBOT in the bimanual and interpersonal task. (Error bars represent ±1 standard error of the mean).



5.5 Discussion

This chapter contrasted intrapersonal and interpersonal performance in a reach-to-target task where both hands/players jointly controlled movement of a single cursor towards different targets that represented either an easy or difficult movement condition for each hand/player. The main result of this experiment was that the relative contribution of the two participants in a dyad did not change across conditions, whereas the relative contribution of individuals' hands changed significantly in the bimanual condition, but only during mismatched trials in which movement was hard for one hand and easy for the other (left and right targets).

In the bimanual task, during mismatched trials, participants made more of the movement towards the target with the hand which was unperturbed (easy) compared to the other (difficult) hand. Thus the right hand produced more movement towards a left target and vice versa for the left hand. This thus represented an asymmetric partition of labour across both hands. This result supported the hypothesis and fell in line with the optimal strategy: by using the unperturbed hand to produce more of the movement, the performance on a trial would be more efficient through avoiding perturbation exposure. For bottom targets, participants opted to use both hands relatively equally (close to zero discrepancy across hands) whilst for top targets there was a slight, but significant, preference for using the right dominant hand. These cases hence represented a more symmetric partition of labour across both hands. Movement contribution for the left and right (unique-difficulty) targets differed significantly from the top and bottom (shared-difficulty) targets because shared targets resulted in symmetric performance whilst targets that were uniquely difficult to one vBOT resulted in asymmetric performance.

To reiterate, in the bimanual intrapersonal condition, both hands contributed relatively equally for top and bottom targets, albeit with a marginal preference for using the dominant hand in the more difficult top target condition. By contrast, for mismatched trials that were uniquely difficult to one hand, there was a clear preference for using more of the unperturbed hand. This pattern of results was not observed in the interpersonal task, however, as performance was similar across all targets. During interpersonal trials, participants were found to contribute relatively equally, despite when this was disadvantageous to do so in terms of efficiency (speed and accuracy) of the task.

Given that trial movements were averaged across the position of both vBOTs and that perturbations were position-dependent, it is interesting to note that for the top target, which was subject to perturbations, individual participants and pairs opted to produce two relatively equal movements using both vBOTs, rather than one larger movement with one vBOT. Moving both vBOTs to the top target exposed individuals/pairs to up to two lateral forces, one per vBOT. The division of work (equally) across both vBOTs suggests that to achieve their goal, players opted for a symmetric 'mirroring' strategy across both hands. Presumably, favouring to deal with (up to two) moderate forces applied to both hands, was seen as more efficient than dealing with a more extreme force applied to only one hand.

Fitts' Law (Fitts, 1954), however, indicates that movement times become lengthened and endpoint accuracy becomes less precise as the amplitude of the movement one is required to make becomes larger. Taken together with the suggestion that the human motor control system is built to minimize endpoint error (Harris & Wolpert, 1998), it therefore makes sense that participants would opt to produce two shorter movements with both hands rather than one larger movement with one hand as optimal control theory predicts this. Furthermore, having to contend with moving against an ever increasing position-dependent force directed laterally to one's intended movement would likely also increase the strength of the motor signal required to produce that action. As the strength of the neural control signal increases, so too does the noise contained within the motor command conveyed to the muscles (Harris & Wolpert, 1998; Sejnowski, 1998). This in turn increases the variability of the motor output, which in the case of reaching towards a target, would make one less likely to accurately hit the target. This would therefore be suboptimal as endpoint precision should be maximized. Accordingly in the current task, participants opted to produce one (interpersonal) or two (bimanual) short movements when moving towards the top target. These same principles could also be echoed to explain the equal share of labour seen across both hands/pairs for the bottom target.

In contrast, for left and right targets, which were difficult for one hand/participant and easy for the other hand/participant, there was a significant difference in performance across task types. Behaviour in these mismatched cases (left, right) were of particular interest in interpersonal task. In the bimanual task, as stated previously during mismatched trials the unperturbed hand dominated the movement when it was easier for that hand to do so. Conversely, in the interpersonal task, performance was similar for both the left and right targets, with both participants contributing almost equally. Hence, whilst the pattern of behaviour in Experiment I conformed to the hypothesis, behaviour in Experiment II did not.

The motor strategies employed during mismatched trials were clearly different across bimanual and interpersonal tasks, therefore making the sources for this discrepancy of particular interest. In Experiment I, participants were exposed to the task with both hands individually prior to their bimanual performance. This was never the case in the interpersonal task, as participants were only ever exposed to one vBOT whose inherent target direction difficulties (either left or right) contrasted with those of the other vBOT in the case of mismatched trials. Participants could hence only infer the difficulties of their task partner using information present in the visual display. For example, if a participant produced a straight movement in an unperturbed field whilst they observed a curved trajectory in the display, it was thought that the participant might have been able to learn to attribute this visual perturbation to be the result of difficulty in the movement executed by their task partner. Other information such the length of time a given trial was taking or the need for secondary corrections too might have aided participants to deduce over the course of interactions which target directions were more difficult for their partner. If it were possible for participants to predict these difficult conditions, under similar target conditions, unperturbed participants might have subsequently made larger displacements so as to reduce the workload of their task partner and also improve the efficiency of the task. In essence, they may have been able to form an explicit representation that could be used for cognitive solutions that optimized task efficiency.

Instead, results indicated that, contrary to the hypothesis, participants in the interpersonal task opted to contribute less towards the target displacement during mismatched trials that were easy for them and hard for their task partner, than compared to participants in the equivalent bimanual condition. In interpersonal mismatched trials, participants favoured sharing the workload across both players. By opting to mirror each other's performance, the perturbed player's movement would certainly have introduced increased error into the averaged outputted cursor displacement, resulting in an increased cost to both players.

Related to this, in their rope-pulling paradigm Braun et al. (2009) participants were also limited to only visual feedback on the performance of the other task partner. When participants performed bimanually they showed cooperative strategies. Dissimilarly, in the interpersonal version of the same game, participants opted for uncooperative solutions.

However, in Braun et al. (2009), participants were not aware of the effects their actions had on the other player and there was also no explicit instruction to cooperate; there was only the instruction to achieve the task goal as 'easily' as possible by minimizing resistive forces. In this current study, in contrast, participants were aware that the position of the cursor was dependent on both players and furthermore they were under explicit instructions to maximize the efficiency of the task overall. This distinction in task instruction might provide some basis for why efficiency (energy cost in resisting forces) was not kept at minimum in this present interpersonal task, although the results remain intriguing given that reducing effort (energy expenditure) is seen as a fundamental motivating principle governing motor actions in individual behaviour (Todorov & Jordan, 2002). Despite being free to choose how to perform efficiently in line the task instruction, behaviour during mismatched trials persisted to be suboptimal (with regards to instructions).

Braun et al. (2011) also later noted that during coordination games which required participants to coordinate their actions together by choosing either the same or opposing strategies, participants were significantly more likely to cooperate to achieve the optimal solution. Worth noting is that in the chicken game (Braun et al., 2011), which required miscoordinated strategies, the evolutionary stable strategy of both players swerving also frequently manifested. In this sense, the current task could have represented a miscoordination game which required asymmetric strategy choice across players. This would partly explain why both participants shared the workload during mismatched trials, as this would represent an evolutionary stable choice. The only other *coordinated* response would have been for both player to not move, which would have left the trial going nowhere and thus been the 'worst' case scenario vis-à-vis task instructions.

Furthermore, Braun et al. (2011) also noted that participants were able to actively explore the payout landscape (which changed over trials) within-trial to achieve coordination. They proposed that a more constant payout landscape would have aided even further by allowing internal models of the dyad interaction to develop through the process described by Wolpert et al. (2003). In the present task, the payout landscape, or more specifically the target locations of greater or lesser difficulty, remained comparatively stable throughout (which the exception of catch trials). Therefore it remains surprising that participants could not predict when to come to the aid of the other player—although, Braun et al. (2009) indicate that the motor nature of certain tasks might attenuate the psychological effects of 'mentalizing' which might otherwise have helped predict the state of the other player.

It is equally possible that participants were simply unable to derive sufficient information from the visual display to build an appropriate representation of their task partner's task difficulty (in addition to their own), leading to an inability to strategize optimal performance as discussed previously. The interpersonal sharing of labour during mismatched trials may also have been due to experience with the top target, as participants were (at least initially) unaware that this target was difficult for both players. Thus, by no player taking a lead role for this top target, a precedent may have been set for behaviour across other perturbed trials, where the task partner's difficulties were unknown. This could tie into the notion of reciprocal altruism, for example (Nowak & Sigmund, 1998; Rilling et al., 2002). In addition, in the individual task, participants had learnt a 1:1 mapping between movement of their vBOT and movement of the cursor. Despite being aware that movements were averaged across both vBOTs in the interpersonal task, participants may have become trained in producing movements of a similar size to those executed in the individual task and they may have incorrectly continued to believe that they were producing the full movement.

Another important possibility to consider is the trade-off between efficiency and equity called 'distributive justice' which commonly materializes during human interactions (Hsu et al., 2008; Sanfey, 2007). One participant doing all the work (i.e., asymmetric task performance) may have been seen as 'less fair' than sharing the effort across both players. Thus the collective responsibilities of each player towards the task, share not only the benefits, but also the burden of that task, even when it is disadvantageous to the overall good of the task. As Hsu et al. (2008) explains, efficiency can actually be perceived as 'wrong' when it disregards a rule or duty. Therefore, it is possible that participants chose to share the workload during mismatched trials because this was simply seen as the fairest option when asked to 'work together'. The concept of 'fairness' is difficult to quantify, however, as one could equally argue that alternating actions across players for left and right targets could have also have been seen as a fair alternative. One suggestion is that tit-for-tat iterated performance or more general temporal concerns regarding convergence among player strategies might influence the quality or nature of the interpersonal performance that unfolds. Sharing labour equally (at least initially) may represent a form of reciprocal altruism which later allows the reputation of co-players to be established (Nowak & Sigmund, 1998; Rilling et al., 2002).

Superficially, behaviour in the interpersonal task may have seemed more selfish than that shown in the bimanual task. However, it is important to note that participants were not idle during difficult target conditions, either. Instead, dyads contributed relatively evenly to movements towards all four targets. Thus, even though participants were perhaps not performing as optimally as they could have been in terms of efficiency and reducing effort (i.e., energy cost), they were still performing cooperatively in line with task instructions by always opting to “work together” regardless of personal target difficulty.

To conclude, the hypothesis that participants would generate more of the shared cursor movement with their unperturbed hand when their partner/other hand was is in a 'difficult' condition only held true in the bimanual task. Whilst neatly capturing performance in the bimanual task, predictions derived from the framework of optimal control did not translate as readily to interpersonal coordination. Interpersonal coordination instead appeared to reflect either a failure to represent the task from the perspective of both players or a strategy which sought to partition the workload equally at the cost of time and effort. Minimizing the cost function through avoiding force exposure did not prevail in the interpersonal condition and instead behaviour favoured equity over efficiency. Future research is necessary to investigate factors mediating the choice of interpersonal solutions that either conform to or violate optimal control theory, with an eye on social as well as motor goals. Specifically, the role of task instructions in governing how participants conceptualize 'efficiency' and 'effort' in the domain of interpersonal motor research may be of importance in ensuring that researchers are in fact testing conditions that are like for like.

CHAPTER SIX

GENERAL DISCUSSION

Through a series of behavioural experiments, this thesis explored how the action of one individual impacts on the motor responses of another individual, when both agents are engaged in a shared task. Accumulatively, the four experimental chapters described in this thesis represented an effort to deepen understanding of the evidence that suggests that humans co-represent their own actions and the observed actions of others in their motor system. On the one hand, a 'common code' (Prinz, 1997) or 'direct match' for action perception (usually externally-generated movements) and action execution (self-generated movements) might allow people to engage in more successful interpersonal actions, as the action of another person can be understood when its observation causes the motor system of the observer to 'resonate' (Rizzolatti, Fogassi, & Gallese, 2001). It may be that this ability to mentally ‘simulate’ the actions of others is key to also allowing people to choose *motor strategies* to help (e.g., cooperative dance) or hinder (e.g., competitive sport) others when appropriate. On the other hand, such a direct match system might also leave people prone to possible interference when observed and executed actions compete for the same representational resources, leading to interference in ongoing or subsequent motor output (Blakemore & Frith, 2005). Furthermore, the direct matching hypothesis raises the question of how people are able to distinguish between the movements of self and others, namely, how is the agency of a movement established? A goal of this thesis was to address some of these issues by probing factors which might modulate the motor representations or motor strategies employed during cooperative interpersonal actions.

In this final chapter, the empirical evidence contained within this thesis will be reviewed against existing research to determine what this work has been able to contribute to current knowledge, whilst also bearing in mind the strengths and the limitations of the methodologies adopted here. Following this, findings will be interpreted with a view to understanding the wider implications of the current results within the study of motor-based interpersonal action. Finally, the discussion will close with suggestions for how research in the area of interpersonal action might be carried forward in future work.

6.1 Summary of Experimental Findings

In Chapter 2, interpersonal action was investigated in a task in which participants were asked to match the frequency of their wrist oscillations with those modelled by a blindfolded experimenter acting as a 'metronome'. The aim of this study was to evaluate the relative contribution of spatial and motoric representations to successful between-person coordination. Previous work had shown that when two individuals are required to coordinate oscillators (limbs, pendulums, etc.), they tend to opt towards one of two stable relative coordination modes: in-phase (0°: oscillators at the same place in the cycle at same time) or anti-phase (180°: oscillators at the opposite place in the cycle at same time) (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990; Schmidt & Turvey, 1994). Moreover, these studies noted that at higher frequencies, anti-phase modes often spontaneously transitioned into in-phase modes, whilst the opposite did not occur, suggesting that in-the phase modes are ultimately a more stable mode for successful coordination at high oscillation frequencies.

The tendency for such phase transitions was experimentally exploited to assess the stability of interpersonal coordination; however, unlike previous work which had conflated the congruency of observed and executed actions along both spatial and motoric dimensions, here these factors were independently manipulated. Spatially congruent movements were those in which limbs oscillated in the same direction of motion, whilst spatially incongruent movements were those in which limbs oscillated in opposing spatial directions. Similarly, motor congruent modes of oscillation were those in which homologous muscles were activated, whilst in motor incongruent modes opposing muscles were activated. Motor congruency in this task thus tapped into the evidence suggesting that there is facilitation of the motor evoked potentials (MEPs) to the specific muscles of the observer that match those muscles used in the observed action, which has been taken to support the notion of shared representations for observed and executed movements (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Maeda, Kleiner-Fisman, & Pascual-Leone, 2002).

Previously, Mechsner, Kerzel, Knoblich and Prinz (2001) had shown that in within-person coordination, participants were biased towards spatially congruent but anatomically incongruent representations as opposed to the reverse situation. This provided strong evidence that perceptual spatial information dominates stable coordination. One goal of the present work was hence to validate Mechsner et al.'s claims to between-person cases. The idea that the strength of representations (whether spatial or motoric) might be subject to modulation from the viewing perspective in which actions were observed was also explored. Including two perspectives (allocentric and pseudo-egocentric) was seen of interest due to conflicting reports on whether anatomical or specular representations are preferentially adopted during imitation and/or the mere observation of movement (Bekkering, Wohlschläger, & Gattis, 2000; Belopolsky, Olivers, & Theeuwes, 2008; Maeda et al., 2002).

Results were consistent with previous literature indicating that in-phase movements were more stable (evidenced in the task by later transition times) than anti-phase movements, as oscillation frequency increased (Schmidt et al., 1990). Furthermore, this was true of both spatial and motor in-phase movements, providing support for the spatial compatibility and the motor interference effects noted previously in motor priming tasks (Brass, Bekkering, & Prinz, 2001). In contrast, no effects of viewpoint were observed, implying that the advantage for spatially and motorically congruent movements during interpersonal coordination persists in both of the perspectives studied, reconfirming the suggestions of Belopolsky et al. (2008).

However, the lack of viewpoint effect observed might also have been a consequence of the fact that the egocentric perspective condition was not a veridical one, and instead it only approximated a real egocentric vantage point. Indeed, the study reiterates the idea that whether an action is represented in an anatomical (motor) or specular (spatial) manner by default may be largely dependent on the structure (e.g., goal-hierarchy, saliency of information) and specific instructions (e.g., imitate, observe, complement) employed in the task design (Bekkering et al., 2000; Franz, Ford, & Werner, 2007). Overall, Chapter 2 demonstrated that a significant advantage for stable interpersonal coordination arose from both motoric and spatially congruent conditions, providing further support for the direct matching hypothesis and disputing Mechsner et al.'s claims that spontaneous coordination phenomenon (phase transitions) are purely perceptually driven during between-person interactions.

Chapter 3 explored performance during sensorimotor synchronization with a point-light display of human movement stimuli derived from the motion recordings of either the participant him/herself or from a gender-matched agent unknown to them (other). There were three key points addressed in this study. Firstly, it was examined whether participants would show a performance advantage when synchronizing with (and correcting for tempo changes in) their own stimuli compared to stimuli of another person, as a self-advantage had already been shown both for recognizing one’s own actions (Beardsworth & Buckner, 1981; Flach, Knoblich, & Prinz, 2004; Knoblich & Prinz, 2001) and for synchronizing with one’s own musical performances (Keller, Knoblich, & Repp, 2007).

Tested secondly, was the notion that top-down information in the form of belief about the agent identity (self, other) of stimuli would also influence performance. It was predicted that participants would show an advantage to synchronizing with stimuli they believed were their own, compared to stimuli they were led to believe were of another person, irrespective of whether this was in fact true. This was based on previous research which indicated that top-down information plays a role in motor priming/performance (Liepelt & Brass, 2010; Stanley, Gowen, & Miall, 2007) when biological versus non-biological agency was highlighted, with interference effects more pronounced during performance in biological-belief conditions noted in both of these studies. This was taken to signify that action simulation is more likely to occur when motion is construed as human, as it is hypothesized that access to the mirroring system is granted through a ‘gating mechanism’ under such conditions (Liepelt & Brass, 2010). Equally, it has been suggested that once the biological implausibility of motion is drawn into focal attention, this motion can no longer be processed as biological and consequently simulation is attenuated (Longo & Bertenthal, 2009). Chapter 3 therefore aimed to extend the agency-belief modulations already reported, by testing *within* the class of biological (self, other) movement.

Finally, the study sought to garner further support for the attention and gating theories posited by Liepelt and Brass (2010). Performance was assessed using measures known to be sensitive at capturing synchronization skill in tapping paradigms and musical performances (Repp, 2005)—specifically, the asynchronies between and discrepancies in the phase durations of participants’ actions and those of the stimuli acting effectively as a metronome.

The results did not show a clear cut agent-self advantage, generally; however, there was evidence to suggest that participants could correct for tempo perturbations more readily when they observed self-generated actions rather than other-generated movements. Significantly, there was strong evidence in support of the hypothesis that there would be a 'self-belief' over 'other-belief' performance advantage. This was seen as less variability in the asynchronies and phase discrepancies between participant and stimulus for self-belief trials relative to other-belief trials. This belief manipulation effect hinted that top-down belief information was specifically modulating performance during trials in which stimuli were in fact those of another person.

Taken altogether, support was shown for attention and gating theories of action-perception and a more detailed description of how Liepelt and Brass' gating theory might function has been provided. It is hypothesized, based on the findings obtained, that motion is initially simulated with one's own highly-tailored motor representation. However, under conditions where motor resonance is weak (such as during agent-other trials), the system undergoes second-stage processing which combines inputs from top-down sources and internal models so as to aid future performance. This is perhaps achieved by relaxing the degree of personalized motor specificity in the motor representations employed, allowing for a more general action representation less prone to motor influence. This hypothesis is critically hinged on the idea that compared to observing the actions of others, less simulation discrepancy occurs for the observation of self-generated actions because these simulations are played out in the same motor system that produced the observed action (Knoblich & Flach, 2003). Overall, it was possible to extend previous research showing top-down modulation of movement during motor priming and motor interference tasks (Liepelt & Brass, 2010; Stanley et al., 2007) to a synchronization paradigm. Furthermore, this top-down modulation went beyond the non-biological and biological differences already reported, to show performance differences amongst self-belief and other-belief (i.e., within-class modulation).

Moving on from examining how action-observation interacts with the kinematics and timing of one's movement, the second half of the thesis (Chapters 4 and 5) investigated the idea that the ability to represent or model the actions of others might have implications for the motor strategies adopted during interpersonal tasks which explicitly require cooperation in order to achieve a common goal as efficiently as possible. These tasks required division of the workload amongst players, which consequently tapped into issues surrounding how individuals balance task efficiency and equity goals during cooperative motor performance.

To this effect, Chapter 4 investigated interpersonal adherence to a robust phenomenon known as Fitts' Law (Fitts, 1954), which characterizes the speed–accuracy trade-off commonly seen in human movement. The law predicts a log linear relationship between the movement time (MT) required to hit a target and the difficulty of hitting that target, given by a function of the target's size and its distance away from the starting point of movement. Briefly, the further away a target is, and the smaller it is, the longer the MTs will have to be in order to accurately hit the target. It was hypothesized that when acting with another person so as to efficiently perform an aiming task, participants would place smaller targets closer to their action partner in order to make their partner's aiming movements easier. More specifically, a linear relationship between target size and placing distance was predicted.

With the exceptions of a few cases (Adam, Mol, Pratt, & Fischer, 2006; Chi & Lin, 1997), Fitts' Law holds well for action production, action imagery and the perception of others' actions (Decety & Jeannerod, 1995; Grosjean, Shiffrar, & Knoblich, 2007). Only recently has research into Fitts' Law been expanded to study between-person cases of movement execution and these studies have produced conflicting reports (Fine & Amazeen, 2011; Mottet, Guiard, Ferrand, & Bootsma, 2001). Therefore, it was felt that further examination of Fitts' Law under interpersonal conditions was justified, however, using a more naturalistic task which approximated the common activity of handing over of an object to another person.

Results were able to reconfirm the previous speed-accuracy relationship reported in Fitts' (1954) original work when participants performed individually during a baseline task, namely that as distances increased and as targets size decreased, MTs increased. The effect of target size was especially evident at further distances, suggesting floor effects for performance in peripersonal space with the large-scale arm movements and range of targets employed in the present task. Also explored was a novel concept, that of *implicit width*, that is, the target area apparently aimed for when performing a placing action with displacement distance at one's own discretion and it is suggested that this may prove useful for future research into Fitts' Law both intrapersonally and potentially interpersonally.

The central result in the interpersonal aspect of the task, however, that was the prediction that target size and placing distance would vary linearly (with the exception of a trend in Experiment I, indicated by the non-parametric Wilcoxon test) was not substantiated. In fact, modelling the task behaviour indicated that participants should have always placed the target either at the distance closest to them (minimum placement) or the distance closest to their action partner (maximum placement). Despite these positions being optimal, real behaviour did not follow this reasoning and instead participants tended to place at distances between the midpoint and the maximum location (i.e., a partially 'altruistic' asymmetric contribution). This pattern of behaviour thus represented neither the optimal solution so as to reduce MTs nor a solution towards an entirely equal split of the workload amongst players. This result highlighted the trade-off between ensuring efficiency whilst also respecting equity (Hsu, Anen, & Quartz, 2008; Sanfey, 2007). The fact that task partners performed slightly more than their fair share, but not so much as to be optimal can be interpreted as a form of altruistic reciprocity, useful at reputation formation and precedent setting (Nowak & Sigmund, 1998; Rilling et al., 2002).

In their work, Mottet et al. (2001) demonstrated that when each member of a dyad took separate charge of either the targets or the pointer movement (and when these objects could be moved simultaneously with respect to each other), participants opted for symmetrical strategies, sharing the relative contribution of movement. This exposes an important difference between the present research and theirs, as in the current task movements were sequential. Participants were working together, but the movement of the pointer was contingent upon the choice of target location determined at the discretion of the placer.

Moreover, Fine and Amazeen (2011) reported a breakdown in obedience to Fitts' Law when participants performed reciprocal movements in the presence of another person who performed similar movements, but with a different index of movement difficulty. Here the participant in the easier condition was found to slow their movements down so as to oscillate more in synchrony with the other person, despite no instructions to do so. This violation effect indicated that the tendency for within-person bimanual synchronization (Kelso, Southard, & Goodman, 1979) also extends to a between-persons setting in which both hands are operated by different people. Conclusions based on this current work and those of others, suggest that task design underpins the observed adherence to or violation of Fitts' Law in observed behaviour. Specifically the temporal and spatial order of events may be key to the dissociations noted in different tasks, not only by encouraging or discouraging spontaneous coupling (synchronization) between individuals, but also by setting in motion socially motivated processes that take into account the fairness or effort of the task to the collective, as opposed to the individual.

Finally, in Chapter 5, cooperative intrapersonal (bimanual) and interpersonal coordination performance was compared during a novel reach-to-target task involving robot manipulanda and a virtual target display. There were four target locations and the relative difficulty of moving towards a given target was contrasted across both hands/participants.

Each hand/participant experienced one shared target as difficult (top), one shared target as easy (bottom) and the other two targets were difficult for one hand but not the other (left, right). Performance in the intrapersonal condition was centralized in that the participants had both visual and haptic feedback on the status of both hands. During the interpersonal task, however, participants could only deduce the difficulty of the other player from the information they could derive from the visual display (i.e., non-centralized). It was hypothesized that over the course of interactions, participants in the easy condition would predict when it was more advantageous for them to make more of the movement towards a target, such as when the other person was in a difficult condition.

Previously, it had been found that participants could learn within-trial how to achieve cooperative solutions to motor variants of game theory tasks (Braun, Ortega, & Wolpert, 2009, 2011). This was despite no explicit instructions to cooperate and task instructions to minimize effort. It was hypothesized that participants in the current task would be able to mentalize about the status of the other player through the visual information available to them about their combined movements. One way to achieve this might be to estimate the hidden state of others in much the same ways as one predicts the state of one's own system as posited in the 'social interaction loop' outlined by Wolpert, Doya and Kawato (2003).

The results of the current task elucidated key differences in the strategies adopted in the intrapersonal versus interpersonal task. Intrapersonal behaviour was both highly cooperative and highly efficient. However, during the interpersonal task there was a distinct social strand to behaviour, demonstrated by equal performance irrespective of task difficulty for individual players. This appeared to show that participants placed value on the fairness of cooperative interactions to the extent that even when instructions were to perform as fast as possible with minimum errors, participants seemingly could not disregard social equity concerns, underscoring the trade-off between equity and efficiency noted previously (Hsu et al., 2008; Sanfey, 2007), however, now within the motor domain. The tendency for partial altruism may reflect the concept of altruistic reciprocity used in image scoring and encouraging subsequent cooperative behaviour (Nowak & Sigmund, 1998; Rilling et al., 2002). Recently put forth is the hypothesis that internal models of perceptual-motor control can serve altruistic functions (Santamaria & Rosenbaum, 2011). Altruistic motor 'etiquette' may be a consequence of the summed actions of two people working together being computed as less than the summed effort of each individual acting alone, thus doing more than one's fair share of the work might not simply be a mark of respect, but also a method of reducing physical effort for the group (Santamaria & Rosenbaum, 2011). If true, this may have had implications for how participants approached the current task.

Furthermore the task may have reflected a form of evolutionary stable strategy, which adds to the argument that these strategies may be better employed than Nash equilibria (Nash, 1950) common in game theory to model human interpersonal motor behaviour, as suggested by Braun et al. (2011). In summary, Chapter 5 provided evidence to the effect that the strategies chosen for individual performance contrast with those chosen for interpersonal performance. Interpersonal performance was characterized by a need for equity *in* efficiency.

6.2 Strengths and Limitations

The strengths of this thesis included both the range of different behavioural testing methods used and the number of different theoretical frameworks considered, particularly perspectives related to action perception and movement control. The motion-tracking techniques used in Chapters 2–4 allowed for high-quality spatial and temporal properties of movements to be analyzed. This allowed relative phase to be computed during the oscillation coordination task (Chapter 2) and also enabled synchronization skill to be qualified by careful monitoring of the timing aspects of movement (Chapter 3). Motion capture also allowed displacements to be measured discretely in Chapter 4, which also saw movement-time data used as a performance measure in a Fitts task. Finally, the position and velocity data obtained from vBOTs (Chapter 5) also successfully allowed for the individual displacements in the direction of a target to be precisely attributed to each player/hand, under conditions where the outputted movement of a cursor was in fact dependent on the summed movement of both players. vBOTs also permitted perturbations to be applied separately to each player/hand so that difficulty levels could vary asymmetrically thus allowing motor behaviour under different difficulty levels to be examined.

Importantly, restricting the study of interpersonal actions purely to the behavioural domain does pose limitations on what can be interpreted at the neural level. As the work contained within this thesis was grounded in the idea that action perception and execution are inextricably linked due to shared representations within the motor system (Fadiga et al., 1995; Rizzolatti & Craighero, 2004), this draws attention to the fact that behavioural work offers only an indirect window into such representations.

Specifically, the key mediator of this simulation hypothesis is suggested to be mirror neurons (see Rizzolatti & Craighero, 2004). To date, only one study has directly studied (via single-cell recordings) neurons in the human brain which display mirroring properties (Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010). Even methods such as functional magnetic resonance imaging (fMRI), which allows brain activity to be monitored during performance, are still indirect, as fMRI relies on a secondary measure of neural activity (i.e., haemodynamic response), which is potentially also largely influenced by individual physiology (Jezzard, Matthews, & Smith, 2001). Furthermore, the reliability of data acquired from fMRI scanners may be distorted by motion artefacts. This imposes large constraints on the types of motor behaviour that can presently be studied with fMRI, making behavioural work still invaluable.

In Chapter 2, the aim had been to examine possible differences arising in the strength of the (motor and/or spatial) representations of observed actions as elicited by two different viewing perspectives (allocentric and pseudo-egocentric). Unfortunately the pseudo-egocentric perspective used in the task (side-by-side) might not have been a truthful depiction of an egocentric viewpoint. This confounds the ability to rule out a modulation of representation strength based on perspective. Furthermore, the experimenter was blindfolded and as such participants might not have been socially motivated or truly *interpersonally* engaged in the task.

In Chapter 3, synchronization was examined; however, the methods were limited as measures were based on the recordings of only one marker (fingertip). Regrettably, this fails to fully portray the true nature of whole-body synchronization, which is core to activities such as military marching, for example. The behavioural relevance of the movement used in the task might also have been a concern as there was a failure to show strong evidence in support of an agent-self advantage. Perhaps the movement chosen was simply too novel to allow simulation processes to be fully exploited, as work by Calvo-Merino, Glaser, Grèzes, Passingham and Haggard (2005) has suggested that sensorimotor experience of an action also increases motor resonance. Had a more recognizable movement (e.g., swinging action) been used that might facilitate simulation, results might have been less ambiguous and potentially also more ecologically valid. Additionally, the tempo changes in the stimuli (and the kinematic changes on downwards movements) may also have contributed to the weak agency effect observed, as temporal movement features may be key to self-recognition (Cook, Johnston, & Heyes, 2011; Flach et al., 2004). The belief manipulation in this task is also a concern, as it cannot be said with certainty that a real 'belief' surrounding the agent present in the display was truly enforced. Lastly, some researchers have also criticized the use of the point-light method in general to study self-recognition, as residual cues (e.g., physique) may be contained within the display (Cook et al., 2011).

Chapter 4 was founded on the incorrect hypothesis that when asked to place a target in position for someone else to hit, that the placing displacements would vary linearly with target size, such that smaller targets would be placed closer to one's task partner. In fact, irrespective of target size optimal placement was either at the minimum possible or maximum possible placing distance (i.e., non-linear). Whether maximum or minimum placement was preferred depended on the target size and also on placing width. Therefore, a mathematical analysis to choose appropriate constrained placing widths so as to ensure differences in optimal position for small versus large targets would have in hindsight been more effective at probing cooperative task sharing behaviour under interpersonal conditions. The reciprocal (reach-and-return) nature of the task was also problematic as the return component of movements weathered the effect of the pointing component during baseline trials. Ideally, fully discrete movements should be investigated in future.

Finally in Chapter 5, during the interpersonal condition in which information regarding the status of one's action partner was limited to what could be inferred from the display, it is possible that participants were unable to derive sufficient information over the limited course of the interactions to allow predictions about the 'state' of the other player. Task instructions to work together may also have implied that both participants be *active* in performing *movement* in the task, despite efficiency being emphasized. Moreover, no feedback on the trial efficiency was given. Had efficiency feedback been given, more exploratory behaviour might have ensued and this might have led to different task solutions which were cooperative *and* efficient (e.g., turn taking).

6.3 Implications and Future Directions

In Chapter 2 both spatial and motor congruency appeared to play a role in stable coordination. The implication for this might be relevant to, for example, sensorimotor training or motor rehabilitation. For instance, is it advantageous for an aerobics instructor to model movements in both a spatially and motor congruent way? Results here suggest so. Equally, in Chapter 3, improved synchronization was noted for self-belief conditions, suggesting a role for top-down modulation of motor behaviour. If attention or instruction can account for improved performance, then this could have tremendous ramifications for how training or physiotherapy might be better employed in future, by, for example, encouraging (or rewarding) attending to movement aspects that might aid performance.

Already discussed in Chapter 3 was a proposed method to tease apart the attention and gating theories of action-perception (Liepelt & Brass, 2010) by biasing attention to specific conditions though reward. Future work should also explore the neural correlates of this gating system and specifically the role of belief in mediating this mechanism, paying close attention to the paracingulate cortex. This area is known to increase in activity for stimuli construed as human in origin, irrespective of whether stimuli was in fact non-biologically plausible (Stanley, Gowen, & Miall, 2010). It would be interesting to probe divergence in the neural activity reported for self-belief versus other-belief, as the data here might predict greater activation in this region dependent on different agency-beliefs within the class of biological movement. To probe the idea of a 'kill switch' mechanism in the gating theory that allows flexible modes of action-representation dependent on the resonance level of observed movements, it would also be especially appealing to verify whether activations of specific regions of the paracingulate cortex are present during conditions when there is a mismatch between true agency and agency-belief (top-down) information.

In Chapter 4, the Fitts task studied was similar to that of Mottet et al., (2001) except that in their task participants were permitted to simultaneously move pointer and targets with respect to one another. In the current task, the movement of pointer (i.e., the participant him/herself) was contingent upon the terminated movement of the placer (i.e., sequential) and furthermore the choice of target location was determined at the discretion of the placer alone. The pointer role in this task was hence not proactive, as pointers were unable to do much to 'improve' task performance. This strongly suggests that the temporal order of events may play a large role in the behaviour that is observed, as, Mottet et al.'s (2001) participants conformed to Fitts' Law, but the participants studied here did not. Future investigation into such dissociations in behaviour through manipulating temporal contingencies might elicit important information regarding when participants choose to behave cooperatively or not.

Both Chapter 4 and 5 also highlighted the equity–efficiency trade-off present when participants are engaged in tasks which require workload to be partitioned amongst players. It seems there is a human tendency towards fairness (Hsu et al., 2008; Sanfey, 2007) and based on work contained in this thesis, this appears to also persist in the motor domain. The semi-altruistic behaviour observed here may reflect the concept of altruistic reciprocity (Nowak & Sigmund, 1998; Rilling et al., 2002; Trivers, 1971) and thus the possibility that 'precedent setting' behaviour played a role could be investigated by utilizing a model to act in either an altruistic or selfish way and observing the subsequent influence this had on other players' performance strategies. Braun et al. (2011) also noted, for instance, that the early convergence of one player to a particular motor strategy may aid the chance of successful coordination.

Comparing and contrasting the neural correlates of the equity–efficiency dilemma in motor behaviour could also shed insight on how computations regarding equality and efficiency in motor tasks are dealt with differently depending on whether the task is performed intrapersonally or interpersonally. Dual scanning techniques (Blakemore, Winston, & Frith, 2004) which enable two individuals to be scanned simultaneously whilst involved in a joint task might be particularly worthy to explore in tasks such as those seen in this thesis.

Finally, to study interpersonal action effectively it may simply not sufficient to study motor behaviour of the individuals in isolation, as there may be emergent tactics that arise specifically under conditions in which another agent is present (e.g., Reed et al., 2006). Therefore, future directions ideally should take a stance towards active-engagement paradigms, involving live agents where possible.

6.4 Conclusions

The work contained within this thesis provides considerable evidence to support the idea that the actions of one individual influences the motor behaviour of another individual when both agents are engaged in a shared task. This assumption derives itself from the suggestion that observed actions and executed actions are represented in a similar manner as posited in the direct matching hypothesis, which implicates mirror neurons as the neural source for these shared representations. Over the course of this work, one is made conscious that the study of interpersonal action is by no means an easy task and great care needs be taken when choosing an experimental design. As exemplified in Chapter 3, even small changes in verbal instruction can potentially have major effects on performance. For a truly comprehensive understanding of interpersonal action, it will ultimately prove advantageous for future researchers to be guided by how different perspectives (social, dynamical systems, motor control etc) and methodologies (behavioural, neuroscientific, etc.) speak to each other in attempting to explain and understand both the machinery and mechanisms which allow intricate and complex interpersonal actions to successfully take place.

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APPENDICES

Appendix One

Figures A and B illustrate typical examples (N = 6) of the MA recovery rates following a tempo change in a perturbed F2S and perturbed S2F trial, respectively. For instance in Figure A, participant LU showed slow recovery with large fluctuations in performance brought about by differences in MAs for upwards (smaller MAs, tending to trail behind the stimuli) and downwards movements (larger MAs, tending to precede the stimulus). By comparison participant XS showed fast recovery with little difference in MAs across the two movement directions. Overall in this F2S example participants' performances tended to precede the stimulus, thus showing anticipatory behaviour.

In Figure B participant LU showed the fastest initially recovery, eventually settling on a stable performance strategy which tended to slightly precede the stimulus. In contrast, participant XS showed a slower initial recovery and eventually settled on performance which slightly trailed behind the stimulus. Overall in this S2F example participants' performances tended to precede the stimulus, thus showing reactionary behaviour.

Figure A Example (N = 6) of MA recovery rates following a perturbed F2S trial

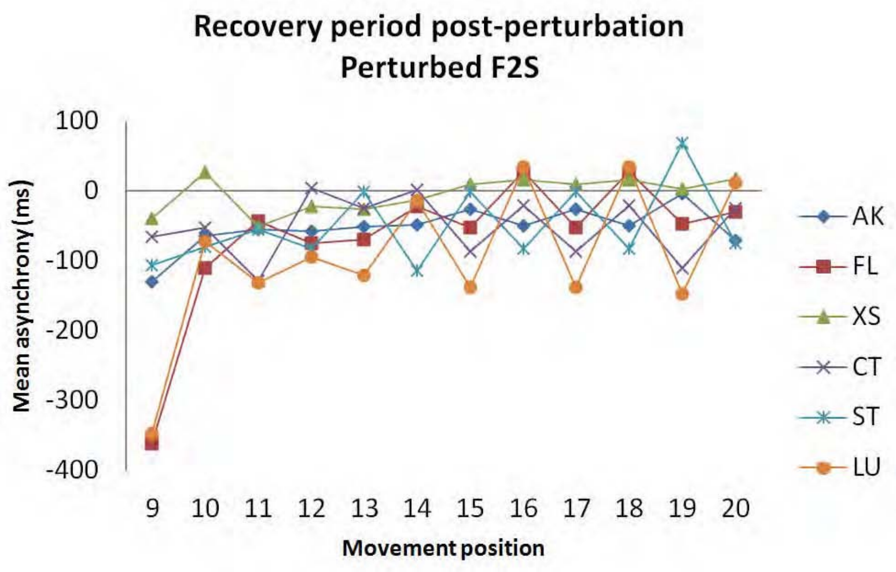
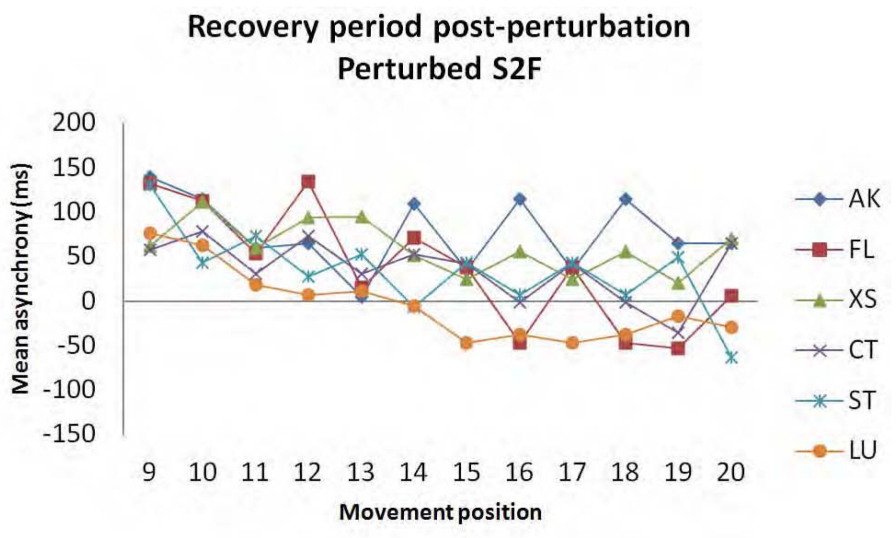


Figure B Example (N = 6) of MA recovery rates following a perturbed S2F trial.



Appendix Two

The apparatus consisted of a wooden board with dimensions 2.5 cm (H) × 53.0 cm (W) × 91.0 cm (L) attached to a table using G-clamps (Figure 4.10). The workspace area measuring 50 cm (W) × 71 cm (L) was covered in 2 × 2 cm grid paper which left 10 cm at either end of the board uncovered where two active illuminated circular electro-conductive buttons (5 cm diameter) were embedded centrally, one at either end of the board. The distance centre to centre of these buttons was 81 cm. Due to the target base diameter and the fact that targets and their bases were not allowed to be placed outside the workspace (i.e. beyond the grid paper), from button centre to target centre the minimum placement distance possible (on the workspace area) was 9 cm and the maximum placement distance possible was 72 cm.

As in Experiment I, markers were drawn on a transparent sheet so that the centre of the middle circle was equidistant from either button centre at a distance of 40.5 cm. The other two circles were drawn either side of the middle circle so that their centres were 17.75 cm away from the centre of the middle circle and 22.75 cm away from the button centre closest to them. Markers were at three fixed distances: 22.75 cm (Distance 1), 40.5 cm (Distance 2), and 58.25 cm (Distance 3), as measured from the centre of the starting button. All other apparatus was identical to Experiment I.

Appendix Three

The apparatus was virtually identical to that of Experiment II. The principal difference to the set-up was the addition of motion tracking equipment to avoid the need for manual measurement of the target placer's displacement of each target. This was done with the intent of making the variable of interest (placing distance) less salient to participants and thus allowing spontaneous placing behaviour to be studied more naturally. The equipment employed was a Liberty electronic motion tracking system (Polhemus, Colchester, VT) with two sensors roughly 1 (H) × 2 (L) cm in size which sampled at 240 Hz each and recorded with a spatial resolution of well under 0.01 cm. The Liberty transmitter was secured to the left hand side of the board (Figure 4.19) with its centre exactly midway down the length of the board (45.5 cm). The only other visible difference in the appearance of the set-up was the removal of the printed 2 × 2 cm grid paper which had previously aided the experimenter in making accurate measurements of the displacements.

The stimuli used in the experiment were the same as used previously except that all targets had now also been equalized for weight (65.7 g), which had not been the case in the two previous experiments. A custom built Matlab (Mathworks, MA) script produced auditory go signals and recorded MTs from the buttons whilst also controlling the motion recordings of each trial. Secured using tape to each participant's right index fingernail was a motion tracking sensor whose cable lead was kept sufficiently slack to allow free movement.