Exploring the effect of avatar and tool appearance on ownership and agency during virtual tasks.

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Impact of COVID-19

This thesis was significantly impacted by COVID-19 in terms of data collection and research direction. Chapter 5, “the effect of delays in a virtual tracking task on the feelings of ownership and agency”, was originally intended as an initial experiment to explore how baseline skin conductance changes with introduced delay, so that further experiments can better account for these changes with an introduced threat condition. Further experiments would have explored different virtual representations with varying levels of likeness to the participant to strengthen the hypothesis that active movement conditions induce stronger ownership illusions that can include tools in a virtual environment. Data collection on this experiment had just begun when the first lockdown was announced, and it would take more than two years before that data collection could continue due to new ethics applications that would allow me to apply the GSR electrodes to participants, which involved touching their hands.

In order to mitigate this delay to my research plan, a new line of research was developed to instead explore virtual tool use and the sense of agency on computer screens, which was able to be tested remotely. For this, I had to learn a new programming language to develop the paradigm. This flexibility opened up an exciting area of research but does mean that the logical flow of experiments was disrupted. I believe that despite this I still ensured that the research's rigour, quality, and validity remained intact.

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Abstract

The feeling of ownership of, for instance, an avatar in virtual reality (VR), can be induced through multisensory correspondences during active body movements. These movements provide a sense of agency which extends to tool use. This thesis explores how familiarity with a tool's appearance affects behaviour and subjective ratings of ownership, agency, and familiarity.

The first two experiments investigated how familiarity with the visual characteristics of a tool affect behaviour and agency. Participants performed a target-pointing task with different computer cursors and rated the sense of agency and naturalness. Ratings were highest with the familiar cursor orientation, which also supported the quickest, most direct movements.

We then varied tool size in VR. Participants completed a pointing task where the size of a virtual hand varied and rated their feelings of ownership and agency. No effects of hand size were found on pointing behaviour or agency, but ownership was higher for the size-matched hand.

To assess the effect of delays on target tracking in VR, participants tracked a moving sphere with a virtual ball, experiencing delays of up to 900 milliseconds between their real movements and the virtual ball movements. Increasing delay led to spatial tracking error and tracking lag. Ownership and agency ratings decreased with increased delay and negatively correlated with tracking error and lag. Baseline Galvanic Skin Responses were significantly affected by task difficulty for large delays.

These experiments show that the appearance of virtual tools significantly affects pointing behaviour and the feeling of agency on a computer screen. This did not translate to less familiar VR settings, suggesting familiarity with a tool's appearance

could drive these results. When a tool does not behave as expected, it further breaks the feeling of agency. Subjective ratings might be linked to perceived task performance, a possible focus for future work.

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Chapter 1: Introduction

1.0 General Introduction

The use of technology in everyday life means that most of us use virtual tools to interact with a computer for large parts of our day. This is especially true since the rise in remote working and online learning since the COVID-19 pandemic (Mali, 2024). To effectively engage with these activities, and for a satisfying experience, users must feel as though they are in control of the virtual tool, the mouse cursor. This means being able to accurately make desired selections. While there may be an element of personal preference in cursor design, the role of familiarity and compatibility with the design of user interfaces need to be taken into account.

There has also been an increase in the use of virtual environments as a tool for rehabilitation (Holden et al., 2005; Viñas Diz & Sobrido-Prieto, 2016), the treatment of pain (Shahrbanian et al., 2012) and even adjustment of social attitudes to gender or race (see Maister et al., 2015). However, for these treatments to work a sense of ownership of the virtual avatars is required.

This thesis focuses on how the appearance of virtual tools, in terms of realism and familiarity, affects performance in virtual tasks, our subjective feelings of ownership over those tools, and agency over the movements.

This chapter aims to define concepts referred to throughout the thesis such as ownership and agency, and will discuss potential mechanisms and previous literature on how they have been studied. Finally, this chapter will bring the information together to put forward the research questions that will be addressed in the rest of the thesis.

1.1 Ownership

1.1.1 Body ownership definition

How do we know that our body is our own? The sense of ownership can be described as the feeling that the body belongs to oneself (Tsakiris et al., 2010) which allows for self-identification (Botvinick & Cohen, 1998) and distinguishes the bodily boundaries from outside objects (Kilteni et al., 2015; Maister et al., 2015). This sense is thought to be the outcome of the integration of various bodily senses such as proprioception (the sense of bodily movement and position, Tuthill & Azim, 2018), vision, and the feeling of touch, that combine to create a unified representation of the body (Kilteni et al., 2015).

As we are unable to manipulate the brain's processing of these sensory signals directly, in order to study this sense of ownership we have to induce an illusory sense of ownership over another, external object, which in turn can be used to manipulate the internal sense body ownership (Haans, IJsselsteijn, & Kort, 2008; Kilteni et al., 2015; Weser et al., 2017). The normally congruent inputs can be disrupted in a systematic way in order to create these illusions so that we can better understand how the sense of body ownership is created by the brain (Sanchez-Vives et al., 2010). Body ownership illusions are therefore a very useful tool for exploring the sense of body ownership (Kilteni et al., 2015).

One of the first documented experiments exploring the sense of body ownership was the Rubber Hand Illusion (RHI) conducted by Botvinick and Cohen (1998). An illusory sense of ownership over a rubber hand was induced by stroking the real hand, which was hidden by a wooden screen and had to be kept completely still, at the same time as stroking a rubber hand placed in front of the participant. The congruency of the sensory input from the seen fake hand and the felt real hand meant that participants reported feeling that the dummy hand was actually their own.

This visuo-tactile paradigm has been used many times since in order to further explore this phenomenon (eg. Armel & Ramachandran, 2003; Haans, IJsselsteijn, & Kort, 2008; see also Longo et al., 2008) and expand it in e.g. the full body illusion (for a review see Kilteni et al., 2015). The illusion relies on the temporal synchrony between seen and felt touch, asynchronous stimulation does not induce the illusion (Botvinick & Cohen, 1998).

1.1.2 Multi-sensory integration

The researchers in the original RHI paradigm concluded that this matching of multiple sensory signals was enough for self-attribution of the fake hand (Botvinick & Cohen, 1998). This matching of the multisensory signals is otherwise known as multisensory integration (MSI).

MSI allows us to form a representation of the world around us, as well as our bodily self. In general perception, we can integrate a visual stimulus, such as a dog jumping around excitedly, with an auditory stimulus, the sound of a dog barking. There may be other dogs nearby not moving in this way, or other noises not occurring in synchrony with the movements, but when the stimuli are close together in time and spatial location it allows us to build a more coherent picture of what is happening around us. In relation to the self, actions and the related feedback still need to occur within a certain amount of time, known as the temporal binding window. Information on the spatial and temporal proximity of the stimuli allow us to bind appropriate stimuli into a single percept (Wallace & Stevenson, 2014).

The subjective experience of body ownership and awareness requires the multisensory integration from various senses (Botvinick & Cohen, 1998; Haggard et al., 2003; Lira et al., 2017; Tsakiris et al., 2007). One example given by Kilteni and colleagues (2015) describes the action of striking a table with your fist, the view of the hand making contact with the table is accompanied by the tactile sensation of the punch. The combination of sensory inputs increases the saliency of otherwise less reliable stimuli, allowing us to more readily prepare to react to external inputs (Ernst & Bülthoff, 2004).

The temporal constraints of the RHI, the need for temporal synchrony, are thought to be part of the same mechanism as for MSI (Constantini et al., 2016). It has been found that the sense of ownership in the RHI diminishes when the delay between seen and felt sensations were over 300ms (which is thought to be outside of the temporal binding window for visuo-tactile stimulation, see for example Bekrater-Bodmann et al., 2014; Shimada et al., 2014).

The brain is able to construct a representation of the environment and the body by calculating the statistical likelihood of a stimulus coming from a particular source, based on the temporal synchrony of various sensory inputs, in a Bayesian fashion (Armel & Ramachandran, 2003). In the RHI experiments, subjects explicitly knew that the rubber hand was not their own, and that they were participating in an illusion, but they still experienced the feeling of ownership over the fake hand. Slater and colleagues (2010) therefore believe that the illusion is a product of the brain trying to make sense of conflicting information.

There are differing views on the processes that drive the rubber hand illusion. These often fall between the dichotomy of bottom up, which is that the illusion is driven by a passive and automatic response to the stimuli (as with visual selection, see

Theeuwes, 2010), and top down, that the illusion is constrained by the expectancy of the participant and their internal body schema.

1.1.3 RHI mechanisms

Botvinick and Cohen (1998) supported bottom-up processing as a mechanism for the illusion. That is, the view that the synchrony of the stimulation was enough on its own to elicit the feeling of ownership over the fake limb (see also Kilteni et al., 2015). In the RHI, asynchronous stimulation causes both the subjective and behavioural measures to happen to a much reduced extent (Sanchez-Vives et al., 2010, Slater et al., 2010). As the seen and felt stimuli happen outside the temporal binding window, they are not combined to create a single percept, and so the assumed locus of the felt stimuli is not thought to be the fake hand. This also means that asynchrony or delayed synchrony are often used as control conditions (Armel & Ramachandran, 2003; Botvinick & Cohen, 1998).

Armel and Ramachandran (2003) also believed that synchrony holds more importance than the visual similarity of the fake body part. In their experiment, it was found that synchronously tapping a (skin textured) plaster on a table at the same time as the real hand was enough to induce the illusion. In this case it is clear that the feeling of ownership is induced by the synchronous touching, as having a patch of table as part of your body does not make sense from a cognitive perspective. Armel and Ramachandran (2003) believed that any object could be experienced as part of the body, as long as the stimulation was synchronous, and that this experience is resistant to top-down knowledge, as participants are aware that the external object is a fake hand or table. If this is the case, it would suggest that the illusion is caused by a bottom-up mechanism, that any object can become part of the self as long as there are strong enough statistical correlations between the different stimuli (Armel & Ramachandran, 2003; Tsakiris et al., 2010).

1.1.4 Top-down modulating explanation

Illusory ownership over non-humanoid objects, however, has generally not been replicated with the passive RHI paradigm and is widely contested (see e.g. Tsakiris & Haggard, 2005; Haans, IJsselsteijn, & Kort, 2008). It is suggested that only objects that fit in with an existing reference model of the body can be assimilated, otherwise known as the “body model” hypothesis (Haans, IJsselsteijn, & Kort, 2008; Tsakiris et al., 2008; 2010).

The body model hypothesis holds that there is an existing body model that allows us to distinguish between corporeal and non-corporeal objects, allowing us to create a coherent sense of self (Tsakiris et al., 2010). It has not yet been determined where the threshold for assimilating physically or posturally dissimilar objects lies (Kilteni et al., 2015). Weser and colleagues (2017) suggest that without this restriction, other objects outside the body could be erroneously perceived as part of the body due to coincidental synchronous stimulation.

Findings have supported that the illusion is also modulated by the top-down internal model of our body’s dimensions (Grechuta et al., 2019). The passive RHI needs the fake hand to be similar enough to the real hand in terms of its physical characteristics (both shape and posture, see Tsakiris et al., 2010; or for a review see Kilteni et al., 2015) and anatomical plausibility (i.e. at an angle that would be achievable by the real limb, see for example Tsakiris & Haggard, 2005; Costantini & Haggard, 2007; Haans et al., 2008).

The feeling of ownership found by Armel and Ramachandran (2003) could have been induced due to the skin like texture of the plaster on the table which was used as the locus of the seen stimulation. Haans, IJsselsteijn and Kort (2008) explored the effect of skin texture with a skin textured sheet in comparison to a plain table, as well as a realistic skin textured fake hand and a fake hand covered with a latex glove. They found no main effect of texture, but that there was an interaction between texture and shape, meaning that realistic skin texture increased the strength of the illusion for the hand shaped object, but not the non-hand-shaped object. They proposed that visual realism of the hand is important for the illusion, which again suggests that there is more at play than simply congruence of sensory input in order to elicit the illusion, and that there are constraints on what objects can bring about the illusory sense of ownership.

It is possible that the two proposed mechanisms for the RHI phenomenon are actually relating to separate processes in the brain. Although often used inconsistently (Longo et al., 2008), there is a distinction between body image, which relates more to the visual appearance and how we perceive our own body (Gallagher, 2006), and the body schema, which is the model of the physical structure and position of the body in relation to how we use it to interact with the world (Dijkerman & De Haan, 2007; see also De Vignemont, 2010).

In order to effectively interact with the environment, the brain has to actively construct the perception of the body (Haggard et al., 2003) making judgements about where limbs are located in space based on visual, tactile, and proprioceptive inputs. These inputs are constantly being integrated by the brain in order to keep the representation of the self as close to the body's current state as possible (Weser et al., 2017) and due to this continuous updating is extremely flexible (Weser et al., 2017; for a review, see Costantini, 2014). This representation has been described as a 'phantom' that is constructed for convenience to keep track of body positioning (Armel & Ramachandran, 2003) as well as forming a boundary between the self and the outside world (Romano et al., 2015; Weser et al., 2017). The RHI then manipulates this sense of bodily boundaries (Haans, IJsselsteijn, & Kort, 2008).

1.1.5 Measuring ownership in the traditional RHI paradigm

Longo and colleagues (2008) propose that there are two aspects of embodiment that are manipulated by the RHI; ownership of the fake hand and perceived location of the real hand. The strength of the ownership illusion is usually measured by self-report questionnaires, such as those used in the original study by Botvinick and Cohen (1998) which try to tap into the phenomenological experience of 'owning' a fake limb. These are typically 8-10 questions long with statements such as "it seemed like the rubber hand was part of my body" (Longo et al., 2008 p.987) and "I felt as if the rubber hand were my hand" (Botvinick & Cohen, 1998 p.756) with responses on a Likert scale. The experience of body ownership is complex, and people may not always have the words to describe what it feels like. Longo and colleagues (2008) used 27 statements when attempting to find a reliable measure of the illusion and found that there was a structure in the pattern of responses from participants that was consistent across experimental conditions. This shows that there was an agreement with certain phrasing that best captured the illusory sense of ownership, such as feeling as though the rubber hand was part of their body.

Measuring proprioceptive drift was an attempt to find an objective measure that did not rely on the subjective reports, which often differed between participants (Longo et al., 2008). Proprioceptive drift measures the three-way interaction between vision, touch, and proprioception, where vision and touch are manipulated, and proprioception is being measured by how much the participants feel as though their real hand is closer to the fake hand than it is in reality (see Botvinick & Cohen, 1998). It can be measured by the participants pointing towards, or placing a marker where they feel their unseen real hand is (Botvinick & Cohen, 1998; Haans, IJsselsteijn & Kort, 2008). Drifts towards the fake body part indicate increased ownership (Tsakiris et al., 2010).

Feeling that body part is in a certain location has been found to be accompanied by a feeling of ownership over that body part (Botvinick & Cohen, 1998). Proprioceptive drift is positively correlated with the subjective measures of the illusion, with increased intensity of the illusion meaning that the participants felt that the location of their own hand had drifted towards the fake hand (Botvinick & Cohen, 1998; Longo et al., 2008, Tsakiris et al., 2010). The participants were not conscious of the occurrence of the drift (Sanchez-Vives et al., 2010).

Different studies also found different results depending on whether the participants were asked to point to where they felt their real hand to be with their other hand, which didn’t differ across conditions (Haans et al., 2008) or to report where their real hand actually is (Tsakiris & Haggard, 2005), which found a difference between conditions with less proprioceptive drift found for objects that didn’t resemble the real hand, but which could be influenced by memory and demand characteristics as this was reported verbally.

There have been reported instances of a dissociation of subjective responses and proprioceptive drift, the increased proprioceptive drift is not always accompanied with a conscious feeling of ownership as measured by subjective responses (Rohde et al., 2011; Maselli & Slater, 2014) which could mean that these are measuring different subcomponents of the illusion, such as the visuo-proprioceptive integration, or possibly a different related phenomenon. Proprioceptive drift has also been shown to happen without the subjective feeling of ownership when subjects have only had visual exposure to the fake hand (Tsakiris et al., 2010). Blanke (2012) has suggested that the feeling of ownership and proprioceptive drift have two different underlying mechanisms.

Proprioceptive drift is a useful proxy measure, but while it is one component of embodiment, it is not directly measuring ownership (Longo et al., 2008). Proprioceptive drift is thought to be caused by an error minimisation process in the brain in an attempt to combine the spatial representation of both the fake and the real hand, which then updates the reference model of the appearance and position of the hand (Lira et al., 2017). This links proprioceptive drift to modifications of the body schema (de Vignemont, 2010), the representation of the body used to plan action, as knowing where our limbs are in space allows us to plan how to move them to complete a certain task. It follows that subjective questionnaires could therefore be more linked to body image, and how we consciously feel our body should look (for example with skin colour, see Lira et al., 2017).

Skin conductance, or Galvanic Skin response (GSR) can also be a measure of embodiment in ownership illusions. An autonomic nervous system response is triggered when the embodied fake hand or object is under threat, in anticipation of pain (Armel & Ramachandran, 2003) where increased response is correlated with increased subjective sense of ownership. This measure is prone to movement artifacts (Lang et al., 1993) but the response cannot be faked (Armel & Ramachandran, 2003).

There have been instances when a physiological response has occurred even though the visuo-tactile sensations were asynchronous, for example when the fake body is realistic and superimposed on its real counterpart (Kilteni et al., 2015). This means that synchronous stimulation may not be needed for the illusion to take place under certain conditions. First person perspective has been shown to be enough to induce the sense of illusory ownership. Slater and colleagues (2010) found that male participants felt ownership over a female body when they were able to see it from the first-person perspective in VR, as well as in conditions of synchronous movement. This was measured by both a subjective questionnaire and heart rate deceleration during a threat scenario, showing that visuo-tactile synchrony is not necessary for the illusion.

The reason behind this physiological response over threat to a realistic hand or body, even in the absence of synchronous stimulation, is thought to be part of the neural basis of empathy. We often mirror the bodily states of others, in order to understand their motivations and actions, which Maister and colleagues (2015) believe shows that the representation of our own body can overlap with that of others. For example, studies found that there was also a drop in heart rate when participants saw another virtual avatar get hurt, in line with the drop in heart rate when it was themselves (Slater et al., 2010).

Ma and Hommel (2013) found that increased skin conductance in reaction to a ball hitting the virtual hand was influenced by top-down expectations and whether the participant felt ownership over the hand. However, a more threatening event triggered a GSR response in a more direct bottom-up reaction, whether body ownership was felt or not. This both suggests that more realistic representations could be causing GSR increases due to empathy and that surprise and fear may also be a factor.

Emotions have a bodily response (Christopoulos, Uy & Yap, 2019), for example both fear and frustration can cause an increase in skin conductance which can be hard to distinguish (Luong & Holz, 2022). Conditions that manipulate the level of ownership using delays, therefore, could also increase the baseline GSR due to an increase in frustration, or a surprise reaction to the representation not behaving in the expected way. This could potentially leave less ‘room’ for a peak during a novel threat, as the baseline skin conductance is already raised.

1.1.6 Embodiment and active movement

There are also fundamentally different ways in which the multisensory correspondences underlying the illusion can come about. For the passive RHI, the cause of the correspondence is external, e.g. when we see and feel someone touch us. The Rubber Hand Illusion has also been shown to work with other sensory inputs, such as correlated visual and motor information. We can generate multisensory correspondences ourselves through active body movements and visually observing our own movements at the same time, as seen in the robot hand illusion, where participants perform movements with their unseen real hand and see the fake robotic counterpart moving in the same way (e.g. Romano et al., 2015; Ismail & Shimada, 2016), and body illusions in Virtual Reality (such as Sanchez-Vives et al, 2010; for a review, see Kilteni et al., 2015).

Virtual Reality (VR) is a very powerful tool for body ownership illusions, and therefore exploring the sense of self, as it allows us to manipulate the fake body part in a way that would be impossible in the physical world, including adding delays between action and on-screen movement, and changing the representation in real time (Slater et al., 2008; 2010). As virtual reality also allows for head tracking, it is believed that participants will respond realistically to the scene presented to them (Sanchez-Vives & Slater, 2005; Slater et al., 2008).

Ownership over the virtual avatar is vital in order to create an immersive experience in VR, therefore body ownership would need to be flexible enough to allow this in order for VR to work. Importantly for the current research, Sanchez-Vives and colleagues (2010) recreated the moving RHI in VR. Using visuomotor congruency they managed to elicit a sense of ownership over the virtual hand, as well as causing proprioceptive drift. Other researchers have also found that the visuomotor illusion has been successful in VR (see for example Romano et al., 2015) and illusory ownership has been achieved for virtual avatars (Banakou, Groten, & Slater, 2013**;** Hägni et al., 2008**;** Slater et al., 2008).

Given this fundamentally different nature, it is possible that these external and self-generated multisensory signals differently contribute to the sense of ownership, and therefore also the strength of the illusion. In particular, the self-generated signals that characterise our experience in everyday control of action would be expected to play a particularly important role for the sense of ownership of our limbs. It can then be argued that eliciting the illusion with active movements is more natural and would create a stronger sense of ownership that could include more than just humanoid objects.

1.1.7 Body ownership and tool-use

The way the body is represented in the brain also allows us to represent the nearby space in order to plan for future actions. If we are using a tool, the space around us that we can therefore interact with is extended. Peri-personal space (PPS) is defined as the area of space directly surrounding the body that is relevant for the interaction with objects and people in our environment (di Pellegrino & Làdavas, 2015) and can be extended to include objects necessary to plan for future action or defend the self (Rossetti et al., 2014, see also Romano et al., 2015). To most effectively interact with the environment, we need internal representations of our limbs and of the external world (Blakemore, Wolpert, & Frith, 2002).

The PPS is informed and updated by multisensory integration, for example in the ownership illusions, the external object (fake hand or tool) is incorporated into the body schema as an extension of PPS by the synchronous tactile stimulation (Romano et al., 2015; Weser et al., 2017).

Body representation is flexible so that we can better interact with the world around us, and importantly means that the body schema can incorporate a tool, which is treated as an extension of the limb wielding it (e.g. Cardinali et al., 2009; Maravita et al., 2002). The area around our body that we are able to influence with our actions is perceived differently, and extending our body with a tool in turn changes the perception of the space at the tip of the tool (for a review see Proffitt & Linkenauger, 2013).

In line bisection tasks, participants have leftward biases in near (reachable) space, and rightward biases in far space (Varnava, McCarthy, & Beaumont, 2002). Longo and Lourenco (2007, p.288) found that there was a shift in biases between near and far space and that there was a “systematic relation between the size of near space and one's body". This can be manipulated with tool use, with the shift in bias being eliminated when using a stick to point as near space is expanded to include the tip of the tool (Longo & Lourenco, 2007). Linkenauger, Bülthoff and Mohler (2015a) have found that changes in perceived distances with differently sized virtual arms only occurs after experience reaching with the arm.

Sensations can be felt through a tool, but it feels as they are coming from the tip of the tool, not through the fingers holding it (Maravita et al., 2002; Weser et al., 2017). Weser and colleagues (2017) believe that this is caused by the rescaling of the representation of the body to incorporate the tool.

Practice with a tool has a place in contributing to embodiment (Rademaker et al., 2014). For instance, for tool-use it is often suggested that proficiency with the tool creates a sense of "being one" with the tool, a phenomenon often observed in sports such as fencing (Biggio et al., 2020). Use of a tool for an extended period allows for the extension of PPS (Bonifazi et al., 2007) and can update the representation of the body in the brain (Cardinali et al., 2009). Enlargement of the boundaries of the PPS has been found to happen after just a couple of minutes practicing with a tool (Farnè et al., 2005). This enlargement only lasts a short time and does not happen when passively handling a tool, and only extends to the functioning part of the tool, suggesting the importance of goal-oriented motor movements (Farnè et al., 2005). This suggests that the ownership of tools, but also a virtual hand, may rely on the proficiency to use the tool/virtual hand and thus repeated exposure in goal-oriented tasks.

Biggio and colleagues (2020) found that task performance increases with increased familiarity with the tool, perhaps because the movements are more natural, and people don't have to think explicitly how to move and use the tool. Practice and familiarity with a tool allow us to predict the tool's movements and how they relate to the input spatially and temporally (Gozli & Brown, 2011). Biggio and colleagues (2020) found that it was the familiarity with a tool that caused the enlarging of the PPS, and this in turn could increase efficiency in processing sensory events around the tool (Gozli & Brown, 2011).

As the PPS is used for preparing for action and interaction with the environment, it follows that active movement conditions, particularly in goal-oriented tasks, would elicit a stronger illusion than passive conditions, particularly for tool use. Dummer and colleagues (2009) found stronger effects of illusory ownership in the RHI with their active condition, rather than their passive condition. Active movement conditions could mean that non-humanoid objects such as tools are assimilated as it is important to represent them when planning actions, with the mechanism being perhaps an extension of PPS.

We therefore propose the existence of a novel, additional, 'fuzzy form' of ownership that does not need a human appearance and can include tools. This proposition is inspired by work suggesting that through the synchrony between active movement and seen movement an ownership illusion was experienced of a handheld tool (Weser et al., 2017) and even to some extent of an abstract shape (Ma & Hommel, 2015; van Dam & Stephens, 2018). The ownership illusion created through self-generated multisensory correspondence may therefore be less particular about visual appearance of the hand or tool.

1.2 Agency

1.2.1 Agency definition

With active movement conditions in the RHI, there is an extra layer of complexity for the feeling of embodiment, in the form of the feeling of agency and the perceived intention to move. The intention to move, if it corresponds with the perceived bodily effects, allows for the attribution of seen or felt actions to the self (Haggard, 2017; Jeannerod, 2003). One definition of the sense of agency is that it refers to the sense of authorship of a given action (Ismail & Shimada, 2016). Gallagher (2000 p.15) describes it as “the sense that I am the one who is causing something to move”.

In order to facilitate active movements conditions in the RHI, paradigms such as the Robot Hand Illusion (for example see Ismail & Shimada, 2016; Romano et al., 2015) and Virtual Hand Illusion (for example see Sanchez-Vives et al., 2010) have been used to study the senses of ownership and agency in these illusions.

The feeling of agency in the moving RHI is often captured using self-report questionnaires such as the one used by Kalckert and Ehrsson (2012) and on-screen rating scales such as those used in van Dam and Stephens (2018). It has been suggested by Kalckert and Ehrsson (2012) that questionnaires in the moving RHI could conflate ownership and agency as they were originally designed to see whether the sense of agency promoted the sense of ownership, so they sought to find a double dissociation between ownership and agency by comparing passive RHI (ownership but no agency), and the moving RHI with both congruent (ownership and agency) and incongruent hand positions (agency but no ownership). This shows that ownership and agency are distinct phenomena and that the questionnaires can tap into them separately. Sensations of movement coming from oneself in passive conditions (when a confederate moves a participant's limb for them, for example) are different to sensations caused by one's own intention to move (David, Newen, & Vogeley, 2008). These illustrate the difference between ownership and agency, as you can still feel that the arm belongs to you, but you are not an agent of that movement.

Romano and colleagues (2015) failed to capture significant feelings of agency towards a robot hand (although there was a trend). One possible explanation for this is that the questions were worded slightly differently to previous moving RHI experiments, such as "it seemed like the robot hand movement reproduced exactly my hand movement" (Romano et al., 2015, p.416). The emphasis of this question being on reproduction of movement, which could have technological constraints, rather than control of movement. Ismail and Shimada (2016, p.3) used questions that better captured the feeling of agency, such as "I felt as if I was causing the movement I saw". In their experiment participants used a data glove to record the movements of their real hand, which was displayed as a virtual hand on a screen, with delays ranging from 90 to 590ms. They found that the feeling of agency was reduced but was still significant with delays of up to 490ms.

1.2.2 Agency models

There are many different models for how the sense of agency arises (for a review, see Braun et al., 2018). During our everyday life we perform goal-oriented actions without thinking, such as reaching for a glass. This intention causes a motor program to start in the brain in order to carry out that action, and if the outcome is predictable (we feel our arm move and end up with the glass in our hand) it gives the person a feeling of agency over that action (David et al., 2008).

This match between the intention and outcome relies on having an internal representation of the movement, a mental map that the brain uses to understand where body parts are in space and what they are doing. This allows a person to move smoothly and accurately (Blakemore, Wolpert, & Frith, 2002). Deficits in this internal forward model causes issues with how movements are controlled and perceived, such as with Schizophrenia (Blakemore et al., 2002, see also Frith, 2005).

An efference copy is a copy of the signal that produces movement that is sent to the appropriate nerves and muscles for producing movement. This copy is also sent to the forward models, which use this to make sensory predictions about the state of the body after the movement and the environmental consequences (Kilteni et al., 2018). This is then compared to the reafferent signals that come back from the movement, such as visual information and proprioception (Jeannerod & Arbib, 2003). This is also known as the comparator model, if the efference copy matches the perceived movement, the feeling of agency arises (Frith, 2005; David et al., 2008). A mismatch between this feed-forward prediction and the actual sensory input would then be an indication that there was an external force at play during the movement.

Another theory for how the feeling of agency arises is retrospective inference, which proposes a less strong involvement of motor predictions. For retrospective inference there has to be three things, first has to be the intention to make the observed action, the intention has to be consistent with the observed action, and finally the intention should be the most likely cause of the observed action (Wegner & Wheatly, 1999; Moore & Obhi, 2012).

There are a few different models again for the most likely cause of the observed action, one of which being the Bayesian Cue Integration theory. The Bayesian Cue Integration Theory suggested by Moore and Fletcher (2012) suggests that there are many different agency cues, all of which are noisy and come with estimate uncertainty, and this theory proposes that these cues are optimally weighted based on the cue's individual precision. It is hard to compute the exact precision of each individual cue, but through studies that dissociate the different aspects of agency these can be estimated. Moore and Fletcher (2012) went on to suggest that prior knowledge can be integrated into the model to create a schema of expected effects. These could be similar to the top-down constraints seen in body ownership.

In Wegner and colleagues' (2004) 'Helping Hand' study, participants stood in front of a mirror with their own hands hidden behind their back, and a confederate stood behind them to be their 'hands'. They found that, if the participants were verbally informed about the next movements, they reported feeling a sense of agency over those movements without having moved themselves. This suggests that the expectation of effect influences the sense of agency.

An example in everyday life (or at least childhood in the late 90's and early 2000's) when we have felt agentic control over something that is actually being controlled by someone else, was when playing a split screen console racing game. At one time we may have been looking at the wrong half of the screen but still felt we were in control of the car we were watching, while actually we were driving into the barrier on our own half of the screen. In this case, the person who was actually in control would have had the same goal as us and would move in a predictable way to stay on the track. There was the intention to drive the virtual car in a certain way, and on the screen we were watching that appeared to be the case, and so the feeling of agency over those movements arose. This would also mean that there was a mismatch in when the buttons were pressed and the movements of the seen car, showing that a certain amount of delay can be tolerated.

Wegner and Wheatly's (1999) 'I spy' experiment showed that priming could increase the sense of agency. In their experiment both the participant and a confederate were in control of a computer mouse and were instructed to point the cursor at one of the on-screen pictures. If the participants were primed with the name of the picture that was then pointed to, they were more likely to feel a sense of agency over that action, even if it was the confederate that made the movement. In this case, the outcome matched the intention, even without the voluntary action.

This "intentional binding" effect (Haggard, Clark, & Kalogeras, 2002) is taken to be a measure of the sense of agency. However, these studies show that there can be temporal binding effects even without the intention to act, suggesting that intentional binding is just part of the more general causal binding, where two events are bound together in time if the most likely explanation is that one caused the other (Buehner, 2012).

1.2.3 Measuring Agency

There is an argument that there are two distinct levels to the sense agency. The Judgement of Agency (JoA) is a higher order and reflective feeling, in contrast to the Feeling of Agency (FoA), which is lower level, implicit and pre-reflective (Synofzik et al., 2008). Recognising oneself as the agent generating a certain thought, or having the conscious realisation that you are the agent of an action, as per Gallagher's (2000) definition of the feeling of agency, could actually be more related to the judgement of agency. Synofzik and colleagues (2008) suggest that the feeling of agency is produced by the weighting of various indicators, and then this is further processed conceptually to make a judgement on attribution. This is arguably retroactive as it relates to ‘conscious will’ (see Wegner & Wheatly, 1999) which corresponds more to JoA, rather than the implicit FoA.

Self-report questionnaires may be capturing the high-level and conscious JoA, highlighting the need for behavioural measures. To produce a measure of the FoA rather than just recording the JoA, there are implicit measures that have been used, such as looking at intentional binding, which is where the intention to make a voluntary action is bound to its physical consequence (such as a button press and corresponding sound being played), causing the subjective compression of time between those events (Haggard, Clark, & Kalogeras, 2002). This happens when the action is voluntary, but not when it is involuntary (Haggard & Clark, 2003). It is suggested that an efference based prediction model binds the intention to act with the expected and congruent outcome (Moore & Obhi, 2012).

It has been found that temporal binding measures and explicit judgements of agency are not correlated (Shwarz et al., 2019). Grünbaum and Christensen (2020) have suggested that there are four levels of agency that are being measured by various experiments looking to manipulate the sense of agency: the phenomenal character (how it feels) against ability (performance accuracy), and internal intention to move the body against external manipulation of events in the environment. They depict the differences and various paradigms in their figure 1A (Grünbaum & Christensen, 2020 p.3). Based on this diagram, the sense of agency this thesis will be referring to is the phenomenal character in relation to manipulating events in the external environment.

1.2.4 Sense of agency and tool-use

The sense of agency can be extended to include the use of tools (Gozli & Brown, 2011). We often use a tool to interact with the world and still feel as though we initiated action and are still responsible for that action. The effect can be quite removed from the physical action, for example pushing a button, as long as the outcome is within expectations we will still feel this sense of agency, we are still aware that we are responsible for that outcome (Haggard, 2017).

Tools transform body movements, meaning that the physical movements needed to operate a tool don't necessarily match the movements of the tool, and that the sensory feedback from the hand movements don't match what is felt through the tool (Wendker et al., 2014). For example, with pliers there is gain that we need to compensate for (Takahashi & Watt, 2014), and there is a shift in plane when using a computer mouse (Brenner et al., 2020). These transformations require mental translation to calibrate the effect of the tool (Takahashi & Watt, 2017), which can happen quickly for simple linear transformations (Wendker et al., 2014).

There also may be a delay in the outcome of the action caused by the nature of the tool. This creates an issue with the Bayesian Cue Integration theory for the sense of agency, as there needs to be a more dynamic and forgiving mechanism to attribute agency for time-delayed actions and effects. This could explain the decreased but not eliminated sense of agency in the moving RHI found by Ismail and Shimada (2016) with agency still significant with delays of 490ms, outside the temporal binding window.

To have sensorimotor control when using a tool, we need to have agency over our own movements and an internal model of the relationship between our own movements and the movements of the tool (Gozli & Brown, 2011).

1.2.5 Agency and the PPS

As the PPS is involved in internal representation of the self and the immediate environment in order to plan future action, it follows that it is also important for the sense of agency. The feeling of agency, especially with a tool, has "further intentional aspects ranging beyond our bodily boundaries" (Braun et al., 2018, p.5).

Often when we are handed a tool, we click it (for example with tongs) or swish a racket to make sure it behaves as we would expect, in order to be able to plan actions with it. If the sense of agency depends on the perceived outcome matching the internal model, knowing how a tool should behave would be important for the feeling to arise. Kalckert and Ehrsson (2012, p.2) describe this as an "initial learning period [that] is required for the arbitrary mapping of action and external effect", and it has been proposed that extended use of a tool expands the PPS (Biggio et al., 2020).

D'Angelo and colleagues (2018) argue that the change in PPS is dependent on the feeling of agency, rather than just familiarity with a tool. In their experiment, they manipulated the size of the PPS by having a virtual hand controlled by the participants further away from the body, or closer to the body than the real hand. They found that the PPS expanded and contracted in relation to the position of the virtual hand, and suggested that this expansion and contraction is caused by the ability to control and interact the world through our own actions.

The expansion of the PPS to include a tool means that the space around the tool's effector is perceived differently. Gozli and Brown (2011) suggest that there is an increased efficiency in processing sensory events around the tool. This would make it easier to use the tool for a specific task and therefore increase task performance.

This means that an increase in task performance when using a tool could have multiple mechanisms; with increased familiarity, a tool may become incorporated into the internal body schema so that users no longer need to think explicitly about the translation between action and effect, as the movements come more naturally. It could alternatively be that the expansion of the PPS and the ability to more effectively attend to events near the effective end of the tool means that users are able to respond more quickly to relevant stimuli.

It has been found that the enlargement of the PPS only lasts a short time and does not happen when passively handling a tool, and only extends to the functioning part of the tool, suggesting the importance of goal-oriented motor movements (Farnè et al., 2005). The active movements provide feedback that would increase the sense of agency and make the internal model more accurate as familiarity with how it behaves increases.

This makes it important to consider task performance, the sense of agency, and the feeling of familiarity when considering the effects of different tools.

1.2.6 The relationship between ownership and agency

We usually experience the senses of ownership and agency together – when moving our body, we feel ownership over the limb and the agency over the movement (Braun et al. 2018). The sense of ownership has found to be stronger when voluntarily initiating movements in the moving RHI (Dummer at al., 2009). In their moving finger illusion, Kalkert and Ehrsson (2012) were able to double dissociate ownership and agency through movements that were voluntary or involuntary (to manipulate agency), congruent or incongruent positioning (to manipulate ownership) and synchronous or asynchronous movements (to manipulate both ownership and agency). They also found that when agency and ownership were allowed to occur together, they were both strengthened.

Tsakiris and colleagues (2006) found that there was more global embodiment of the hand when agency was felt over single finger movements. That is, when actively moving the finger, rather than during passive stimulation, the sense of embodiment was not restricted to just that finger. This further shows that the sense of ownership is modulated by agency and active movement conditions.

It is unclear whether this modulation of ownership is caused by the efferent motor signals or the sense of agency itself (Braun et al., 2018). Grechuta and colleagues (2019) suggest that body ownership comes from our brain predicting and receiving feedback about our movements, influencing both our sense of owning our body and how well we perform actions. Therefore, planned actions and their sensory effects are important indicators for body ownership as the brain can test these against predicted outcomes (Braun et al., 2018).

When considering goal-directed movements, manipulations aimed at reducing the senses of ownership could make tasks inherently harder, as they would reduce the familiarity with the way the body part looks or moves, which would require more mental translation to integrate into existing schemas.

1.3 Research aim

The main aim of this thesis is to explore the effect of avatar and tool appearance on ownership and agency during virtual tasks. The virtual tools are representations of our movements in the virtual space and include mouse cursors in a 2D space (on a computer screen) and representations in a 3D virtual environment that track the movement of the user. These can vary from a very simplistic ball representation to more complex hand representations that can match finger movements as well as positioning within the space. We are interested in how changing the appearance and behaviour of these tools change user behaviour in the tasks along with the reported feelings of ownership and agency. In order to do this, we will address the research questions which are split into two groups: familiarity and agency with virtual tools; and agency and ownership with virtual representations, as laid out below.

1.4 Research questions

1.4.1 Familiarity and agency with virtual tools

Mouse cursors are a valuable tool as there needs to be a representation of real-world movements made by the user, providing a viable indicator of what is going to be selected on the screen (Dix et al., 1998). While there is likely to be little to no embodiment or ownership of the tool in the case of mouse cursors, we nevertheless want to assess how the familiarity with visual characteristics of a cursor interacts with unfamiliar orientations, and how this might affect agency in on-screen tasks.

Does computer cursor orientation and visual characteristics affect pointing behaviour and the sense of agency in a target pointing task?

This question is considered in Chapter 2. Through presenting the cursor at unfamiliar rotations, this study explores whether any change in task performance is due to just familiarity with the cursor image, or if it is also affected by the feeling of agency. Participants will be asked how natural the cursor feels to them with the different visual characteristics, to tap into the intuitiveness of mouse and cursor use that comes from regular computer use.

Does cursor size affect the feeling of agency and behaviour in a target pointing task?

Further to the familiarity with the shape, familiarity with the size of a tool may also affect the feeling of agency and pointing behaviour. This is considered in Chapter 3 using an on-screen pointing task. This considers another component of familiarity and introduces the concepts of stimulus-response compatibility (Fitts & Seeger, 1953) and Fitts' law (Fitts, 1954), which both consider how the visual characteristics of the tool relate to the task, in terms of relative target size and location.

1.4.2 Agency and ownership with virtual representations

We want to consider what constitutes a cue for ownership when completing a task in virtual reality, such as visual appearance (relating to and based on similarity to body image), and multisensory correspondence of the body or limb (e.g. spatio-temporal congruence and potentially the adaptability thereof). Ownership was measured in a similar way to the RHI paradigm, by asking participants how much they felt that the virtual representation had become part of them. This could extend to non-humanoid tools in the same way that athletes 'become one' with a tool they use often.

Does familiarity with a tool's size also affect the sense of ownership and agency in a pointing task in a virtual environment?

A virtual hand, even if it moves and appears like a real hand, can be considered a tool for interacting with the virtual environment. Chapter 4 looks at whether changing the size of this tool has an effect on pointing behaviour and the feeling of agency over the movements. Further to the on-screen tool use experiments, the active movement in a 3D space could also induce the sense of ownership over the tool as part of the body, so we are also interested in how the change in size affects this sense of ownership.

Does task performance in a virtual tracking task with added delays directly relate to the subjective feelings of ownership and agency?

Chapter 5 looks at whether reducing the synchrony of movements in a virtual tracking task by adding a delay affects task performance as an objective measure and compares that with ratings of ownership and agency. The strength of the RHI in visuomotor conditions should mean that non-humanoid tools are incorporated into the body schema, but this could directly relate to the amount of delay introduced.

Do manipulations that affect the sense of ownership, such as asynchronous movement conditions, also cause baseline skin conductance to increase?

In chapter 5 we also introduce GSR to explore whether conditions intended to reduce the feeling of ownership through asynchronous stimulation, i.e. there being a delay between felt movement and movement of the representation in the environment, may also change the baseline skin conductance. This could be through an association with increased ownership due to the increased salience in congruent conditions, or increased frustration or effort needed to complete the task in delay conditions as they are objectively harder.

Chapter 2: The effect of cursor image and orientation on pointing behaviour and the sense of agency

2.0 Abstract

The sense of agency is the feeling of authorship over our own actions. This can extend to tool use, including the feeling that we are in control of a virtual tool, such as a computer mouse cursor, when we move the physical mouse. This study investigates how familiarity with the shape and orientation of the tool affects behaviour and these feelings of agency. Participants performed a target-pointing task, whereby they moved the cursor to click targets at 8 different locations as quickly and accurately as possible. The cursor was either an arrow or hand shape of varying rotations (45°, 135°, 225°, and 315°). After a set of 8 trials, during which the shape and orientation of the cursor stayed constant, participants answered questions on the level of agency they felt over the movement and how natural the cursor felt. This was repeated for all cursor types and rotations in blocks, with each block repeated a total of 5 times. Results show that fastest completion times were found at familiar cursor rotations (45°). There was more deviation from a straight path to targets orthogonal to cursor orientation for both cursors, with the arrow cursor being more affected by orientation. Participants felt the most agency towards the arrow cursor pointing to the familiar top left (45°). The level of familiarity of the arrow cursor was significantly affected by orientation, but this was not the case for the hand cursor. These results show that even in a simple pointing task, cursor appearance and familiarity affect both pointing behaviour and the feeling of agency.

2.1 Introduction

When we decide to move part of our body and it moves accordingly, we get the sense that we caused that movement (Gallagher, 2000). This is the sense of agency (SoA) which refers to the experience of initiating and controlling an action (Moore & Fletcher, 2012), giving the person a sense of authorship over that action (Ismail & Shimada, 2016) and control over the external environment (Sidarus et al, 2017).

This sense of agency arises when the sensory feedback from the movement matches the intended outcome. This match between the intention and outcome relies on having an internal representation of the movement, an internal or motor model, which is a mental map that the brain uses to understand where body parts are in space and what they are doing. This allows a person to move smoothly and accurately (Blakemore et al., 2002). The intention to move, if it corresponds with the perceived bodily effects, allows for the attribution of seen or felt actions to the self (Haggard, 2017; Jeannerod, 2003).

Further models have also combined the sensory information being received with prior knowledge about the movement in a Bayesian manner; agency arises when the most likely cause was oneself, given the intention to move as a prior (Moore & Fletcher, 2012).

These models can be extended and applied when we use something that is not part of our body to complete a task. The sensory signals received from a tool can be matched with perceived outcomes in a similar way to our own body. The feeling of agency extends to tools when the movements that they make are immediate effects of our own movements (Gozli & Brown, 2011).

We often use a tool to interact with the world, for example using an elongated duster to extend our reach, a spoon to stir food that is too hot, or even a car to travel further and faster than we could naturally (see also Raima et al., 2020 who explored agency when operating heavy machinery). When we use those tools, even though our actions are not having a direct, unmediated effect on the environment, we still feel as though we initiated that action, and we are still responsible for that action. To have sensorimotor control when using a tool, we need to have agency over our own movements and an internal model of the relationship between our own movements and the movements of the tool (Gozli & Brown, 2011).

To build the internal model of the tool as an extension of the self, we must have experience of how the tool behaves. Using a tool means that our information processing system needs to integrate discrepant sensory feedback from the moving hand and the sensory feedback from the effective part of the tool, which happens quickly for simple linear transformations (Wendker et al., 2014).

Practice and familiarity with a tool allow us to predict the tool's movements and how they relate to the input spatially and temporally (Gozli & Brown, 2011). When handled enough, a tool can become an extension of the human body, a phenomenon often observed in sports such as fencing (Biggio et al., 2020). Biggio and colleagues found that task performance increases with increased familiarity with the tool, perhaps because the movements are more natural, and people do not have to think explicitly how to move and use the tool.

The improved task performance could be explained by an enlargement of the boundaries of the peri-personal space (PPS) after practicing with a tool, which has been found to happen after just a couple of minutes (Farnè et al., 2005) and which increases efficiency in processing sensory events around the tool (Gozli & Brown, 2011). This enlargement only lasts a short time and does not happen when passively handling a tool, and only extends to the functioning part of the tool, suggesting the importance of goal-oriented motor movements (Farnè et al., 2005). Biggio and colleagues (2020) found that it was the familiarity with a tool that caused the enlarging of the PPS. D'Angelo and colleagues (2018) argue that the change in PPS is dependent on the feeling of agency, rather than familiarity. They suggest that the expansion and contraction of the PPS is caused by the ability to control and interact the world through our own actions.

Anecdotally it has been noticed that when we are handed a tool, we click it (for example with tongs) or swish it to make sure it behaves as we would expect. Objects like tongs and pliers change the mapping between object size and hand opening reducing the reliability of haptic feedback, causing the visuo-motor system to adjust with new sensory information and increase the reliance on visual feedback (Takahashi & Watt, 2014).

The above can also be applied to virtual tools, like those used to interact with a computer or games console. Most of the population of industrialised societies are used to using a computer mouse, particularly with the rise in remote working and online learning since the COVID-19 pandemic (Mali, 2024). It is unobtrusive, natural and intuitive to move the cursor to where we want it (Brenner et al., 2020), and we often forget that there is a mouse between us and the screen.

Mouse movements and cursor movements are not 1:1, there is gain or velocity programmed in for user experience. Users can quickly build a reliable internal model of this mapping (Gozli & Brown, 2011). When using an unfamiliar PC or a game with more sensitive mouse movements, we can quickly modify our own movements to compensate for this.

Typical PCs are set up with a mouse operating on a horizontal plane, with the cursor appearing on a vertical screen (Dix et al., 1998). Although the mapping between mouse movements and on-screen movements needs to be calculated, people have been found to be faster on a vertical screen than on a tabletop screen (Pavlovych & Stuerzlinger, 2008).

Brenner and colleagues (2020) conducted an on-screen target pointing task while varying the orientation of the surface in space and the orientation of the mouse in the hand. They found that pointing times were faster when the motor mapping was familiar, i.e. extending the arm moves the mouse upwards on the screen, even when this was extending the arm out to the side (although the most familiar configuration had the fastest time for most participants). This was followed by movements that mapped the movement of the mouse along a surface to the movement of the cursor on the screen.

In the case of cursor use, visual information is given more weight that proprioceptive information for the control of action (Wendker et al., 2014). In a task where cursor movements deviated at an angle from mouse movements, Fourneret and Jeannerod (1998) found that participants forget where their hand is or underestimate the amount of deviation between seen on screen movements and their hidden hand, suggesting that participants are not aware of the sensory feedback from their own hand movements.

Both of these suggest that we are not visually or proprioceptively attending to the feedback from the actual movement of the hand relative to the body, but instead have an internal model; we know that moving the hand holding the mouse in a certain way should move it on the screen in a certain way. Predicting this movement accurately should both increase pointing efficiency and the feeling of agency over the movement.

When using a tool in an unfamiliar way, such as getting used to driving on another side of the road, or getting used to new operating system on a computer, we have to keep making adjustments to overcome entrenched habits (Chong, Kee & Chaturvedi, 2015). Changing the size or behaviour of the tool means having to construct a new internal model, which does not eliminate agency but may reduce it (Gozli & Brown, 2011).

The aim of the present study is to investigate how familiarity with the shape and orientation of the tool (in this case a mouse cursor) affects behaviour and the feeling of agency, without changing the responsive behaviour of the tool. To do this we created a target-pointing task on a computer screen, with cursors that vary in shape (a hand image or an arrow image) and orientation (45°, 135°, 225°, and 315°). Participants could move the cursor to click targets at 8 different locations as quickly and accurately as possible and then answered questions relating to agency and familiarity on a sliding scale.

Since the responsive behaviour of the mouse is as expected, just the visual component can have an effect on task performance in this task.

We expect to find that the arrow shaped cursor at 45° rotation (pointing towards the top left of the screen) will have the best task performance as this is what participants are generally most familiar with and will also produce the highest ratings of agency over the movement.

The hand cursor is less familiar to computer users, since the arrow cursor is more widely used (Po, Fisher, & Booth, 2005). However, the hand shape is more familiar in terms of biological congruence, it is more similar to the actual hand. This experiment will explore further whether the task specific familiarity of computer use has more of an effect than general familiarity with a biologically congruous shape.

In the moving rubber hand illusion (mRHI) and the robot hand illusion (RoHI) participants perform movements with their unseen real hand and see the fake or robotic counterpart moving in the same way (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012; Romano et al., 2015; for a review, see Kilteni et al., 2015). Researchers found that participants gave higher ratings for agency over the movements of the fake hand when the fake hand was in an anatomically congruent position (Kalckert & Ehrsson 2012), although when the fake hand is positioned at incongruent angles to the real hand, the feeling of agency is still present.

This shows that not only the appearance of the hand is important, but also it's positioning in relation to the real hand, which could be extended to computer screens. If there is a hand shaped cursor that is not in a biologically congruent position (for example, pointing towards the participant) then the feeling of agency over the movements may be reduced. This could also apply to the arrow shaped cursor if we think of the arrow as a pointed finger.

Further, if participants see the mouse cursor as a representation of their hand, a more realistic cursor may provide participants more tolerance to unfamiliar changes, as long as those changes are anatomically congruent (e.g. the cursor being rotated to an angle that is plausible, albeit uncomfortable).

2.2 Method

2.2.1 Participants

The study was approved by the Ethics Committee of the Department of Psychology at the University of Essex prior to data collection (ethics code: ETH1920-1719). The participants were naive with respect to the purpose of the experiment and informed consent was obtained from each participant through Qualtrics.

Participants were psychology students who were recruited for course credits (N = 22, aged between 18 and 44 (M= 22.23 SD= 4.26)). Power considerations are included in Appendix A.

Participants were then redirected from the participation system to the Qualtrics survey.

2.2.2 Demographic data procedure

Through Qualtrics participants self-reported demographic information (age, gender etc). As part of this participants also self-reported which hand is their dominant hand (the options were “left”, “right” and “both the same”) and then which hand they usually use to control a computer mouse. The survey also instructed participants to use the mouse in their usual hand while completing the experiment. All participants reported that they were right-handed. It was assumed that the monitor and mouse position at the time of the experiment were optimal or familiar to the participant. This may not have been the case if the participant was using a shared space (see Wigdor et al., 2006 who discuss the effects of this).

Qualtrics furthermore gathered information about the device used, such as which browser, version, operating system, screen resolution, flash version, and java support. Participation using a mobile device was prevented, only allowing those using a laptop or PC to participate. Participants completed a short task to estimate their screen size and resolution (number of pixels per mm). Participants were instructed to place a credit card, which have a standard size of 85.60mm x 53.98mm, or similar card of the same dimensions, at an indicated place on the screen and told that they need to move the mouse to match the size of a rectangle to the size of the credit card. Mouse movements caused a rectangle on the screen to become larger the further away the cursor was moved from the origin point, allowing participants to accurately report the amount of screen space that was equal to a standard credit card.

After the short Qualtrics survey participants were automatically taken to the Pavlovia platform (Pavlovia.org) where the actual experiment, i.e., the pointing task, took place.

2.2.3 Stimuli

The pointing task was programmed using the experiment builder for PsychoPy[3] and its semi-automatic translation to javascript, i.e., PsychoJS (Peirce et al., 2019; Bridges et al., 2020). This code was uploaded to Pavlovia.org using the experiment builder for running the experiment online.

The experiment did not use absolute coordinates in terms of cm or pixels, which is why henceforth all measurements will be in arbitrary units (a.u). The experiment is set to use 'height units' which are relative to screen size, with the screen height being 1 a.u., meaning that for a standard widescreen (16:10 aspect ratio) the bottom left of the screen is (-0.8,-0.5) and top-right is (+0.8,+0.5) (PsychoPy, 2024). The visual stimuli were presented relative to screen size as making them fixed physical distances (i.e. the same retinal size for all participants) could mean that some targets would be presented off-screen for some monitor sizes.

Two cursor images were used, an arrow shape and a hand shape (see figure 2.2.1). The cursors were fully transparent (0% opaque) except for the outline (100% opaque), allowing participants to see items that would otherwise be obscured (such as the starting crosshair and targets). It has been found that viewing information through cursors doesn't hinder performance (Worden et al., 1997). The hotspots were at the vertex of the arrow cursor and the tip of the index finger of the hand cursor. The arrow cursor was symmetrical to allow for rotation, similar to the one used by Po and colleagues (2005). The cursors were presented at 45°, 135°, 225° and 315° rotations, with 45° being the familiar top left, as the experiment builder calculated these anti-clockwise. The cursor movements were mapped to the movement of the physical mouse.

Pointer acceleration is implemented on all major operating systems (Müller, 2017), meaning that if a user moves the mouse the same distance, but with different speeds, the distance the cursor on the screen travels will differ. No improved performance has been found for those using variable gain mice (Jellinek & Card, 1990) so no compensation was made for acceleration of the mouse movement.

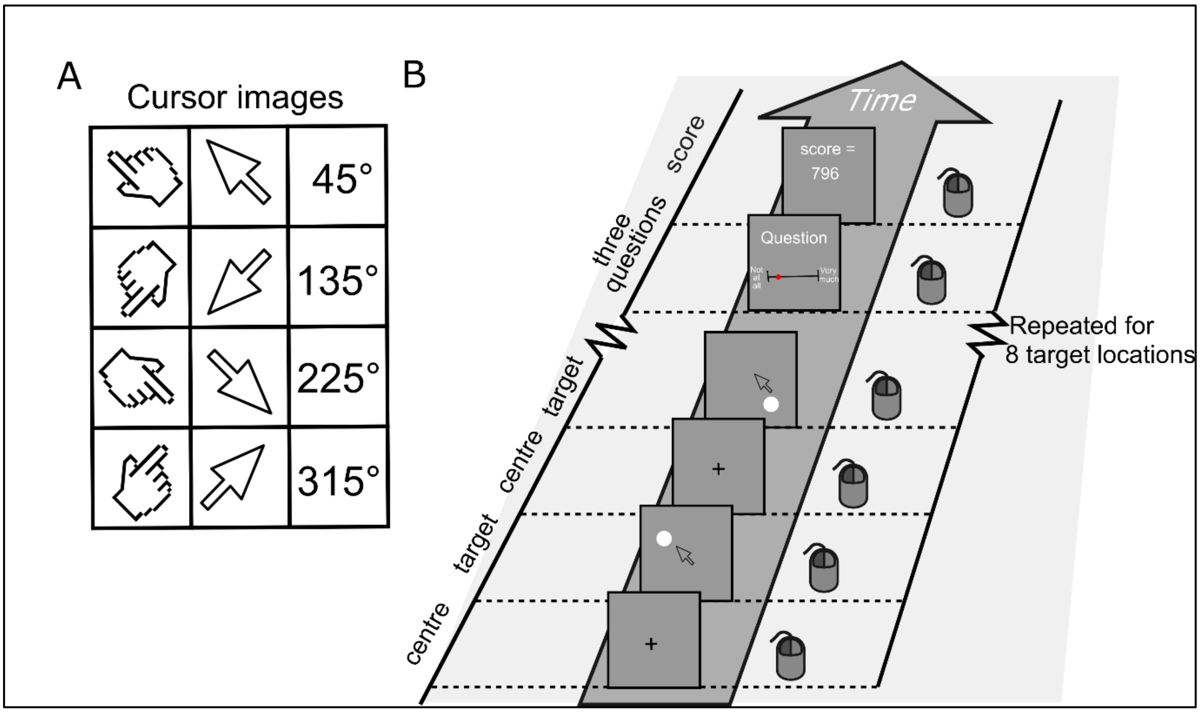

Figure 2.2.1: **A** shows the cursor images at height 0.1a.u. and rotations used, the hotspots are at the tip of the index finger and tip of the arrow. **B** shows the procedure for each block.

2.2.4 Procedure

Participants were instructed to click the target (a white circle with a constant diameter of 0.05 a.u.) "as quickly and accurately as possible" using their computer mouse. Participants initiated each pointing trial by clicking a central marker (a plus '+' symbol with size 0.02 a.u.). This ensured that all trials started with the cursor in the centre of the screen. Once participants had clicked the central marker, the first target for that trial was shown and the cursor image changed corresponding to the specific cursor condition for that trial (i.e. hand or arrow cursor and its specific orientation).

The targets appeared at 8 locations spaced evenly around the central marker, (r = 0.3 a.u.) presented at 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° (cardinal and intercardinal points) in a random order.

The trials ended with a left mouse-click, even if the target was not reached. Upon left-click the target disappeared, and the central marker reappeared to start the next pointing trial.

For each trial, the movements of the mouse cursor were recorded with a sample taken at every browser frame. The positions of the cursor click were also recorded.

Each block contained 8 pointing trials (one for each target location) followed by the ratings scales at the end of each block. The cursor stayed at a constant image and orientation for the whole block so that the ratings for that block would then correspond to one particular cursor type and rotation.

The feelings of agency and familiarity were measured using rating scales presented on screen. The first question targeted the level of agency the participant felt: “I felt I was controlling the cursor”. The second question is a control question relating to agency, “The cursor seemed to have a will of its own” and participants are expected to give the reverse ratings to Question 1. The third question is measuring familiarity, “The cursor felt natural to me”. The scale was presented along the x-axis, from -0.4 to 0.4 and went from “Not at all” to “Very Much” in a continuous manner. A red dot appeared on the scale and participants indicated their rating by moving the dot to the desired position using the mouse. Responses were recorded upon click.

Such on-screen rating scales have been shown to work in virtual reality (van Dam & Stephens, 2018) and are based on the questions used by Kalckert and Ehrsson (2012) to measure the sense of agency in the moving rubber hand illusion. The results from the on-screen scales have been shown to strongly correlate with results from multi-item questionnaires (van Dam & Stephens, 2018) and so they are likely measuring the same phenomenon.

After providing the ratings, participants were shown their score based on the distance from the centre of the target across 8 trials in the pointing task, with the message “Doing Well! Your score in the last block was (score)”. This completes the block. The score was shown for motivation purposes to keep the participant attempting to be as accurate as possible as well as to promote a sense of agency (Wen et al., 2015a).

To provide this score, the absolute error was calculated between the target coordinates and the click coordinates. The trial score was then calculated based on the exponential function of the negative squared absolute error, then scaled by 100 and rounded to the nearest integer. The block score was updated with each trial score, then used to display the message at the end of each block.

This procedure was repeated for both cursor types (hand and arrow) and all four cursor rotations in blocks, with each block repeated a total of 5 times, to make a total of 40 blocks for the experiment. The blocks were presented in a randomised order to counterbalance and attempt to rule out any order effects.

2.3 Movement analysis

<u>The analysis was not pre-registered.</u>

<u>2.3.1 Trial removal</u>

The analysis code checked if movement trials needed to be excluded based on whether the target was reached, as well as based on other time constraints, detailed below. These triggers were only set for trial removal and did not form part of the analysis, where the whole movement path was considered.

The trigger for movement onset was set to 10% of the straight-line path length from the starting point to the target when the speed was also above threshold (a fixed value of 0.05). The movement offset was triggered when the movement path length remaining to the target was less than 20% of the straight-line distance and the speed was below the speed threshold. If onset or offset point parameters were not met, then the whole movement path was marked for removal for that trial.

Trials were removed if the participant did not click the target, or if there were fewer than five samples in the cursor path (i.e. the path was too short, which often represents a miss click). Trials were also removed if the participant waited too long to complete the movement (more than three seconds from start of trial until mouse click) or if the movement itself took too long (more than two seconds between movement onset and mouse click).

Lastly, individual trials were removed if the movement onset or completion time was more than three standard deviations away from the overall mean across all trials for that participant.

A total of 11.4% of trials were removed due to not meeting above parameters, and a further 2% were removed as outliers.

Participants were excluded completely if there was no data at all for any combination of: cursor identity; cursor orientation; or target location. In this case, two participants were removed from the movement analysis due to these criteria.

The ratings for a participant were removed if a t-test revealed that there was no significant difference for the answers given in the agency rating question (Q1) and the agency control question (Q2) for that participant, since this suggests that the participant was not paying attention to the questions when providing the ratings.

However, the movement data were still analysed in these cases as long as they did not meet any of the other exclusion criteria. Four participants were excluded from the ratings data (further to the two participants excluded from the whole analysis). None of these participants consistently rated the feeling of agency close to 0.

2.3.2 Completion times

Completion time was calculated from when the target appeared until the mouse was clicked.

2.3.3 Path deviation

In order to analyse the deviations and movement path relative to the target, the target angle was calculated and movement path data rotated to align movement towards the target with the x-axis and deviations from straight-to-target path on the y-axis. The movement trajectories were resampled taking percentage points (10%-95% in steps of 5%) along the x-axis (in rotated spatial terms). This creates a smooth path by estimating the y-coordinates at specific percentage points along the movement path, ensuring the path doesn't have abrupt changes and follows a predictable curve. The y-value at mid-point on the x-axis towards the target was taken as the deviation half-way in the movement and stored for further analysis. For calculating average trajectories, the interpolated coordinates rotated back to the original coordinate system before averaging across trials from the same condition.

2.4 Results

2.4.1 Completion times

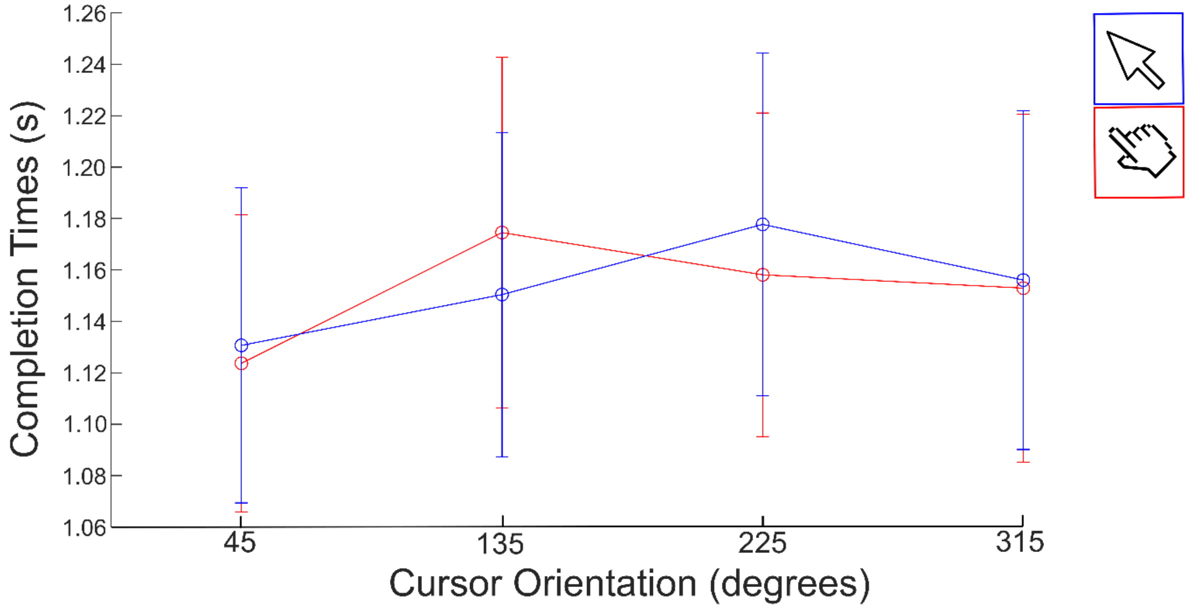

Figure 2.4.1 shows mean completion times for each cursor orientation in seconds. Error bars show the standard error.

Participants were asked to click the target as quickly as possible. Completion times were measured from target onset to mouse click and considered to see if the different cursor image or orientation affected how quickly a participant could complete the task. We expected to find that the arrow shaped cursor at 45° rotation (pointing towards the top left of the screen) would have the best task performance.

A two-way 2x4 repeated measures ANOVA was conducted in Matlab (Trujillo-Ortiz, 2021a) to see whether cursor image (2) and cursor orientation (4) affected trial completion times. There was a main effect of cursor orientation $F(3,57) = 6.17$ $p = .001$. To investigate this further, multiple comparisons were performed. These revealed a significant difference between cursors at 45° and 135° ($t(19) = -3.35$; $p <$

.05), between 45° and 225° (t(19) = -3.31; p < .05) and between 45° and 315° (t(19) = -2.23; p = .038). This means that participants had significantly faster trial completion times for cursors pointing to the familiar top left. There was also an interaction between cursor image and cursor orientation (F(3,57) = 2.87, p = .036).

There was no main effect of image (F(1,19) = 0.05, p = .835).

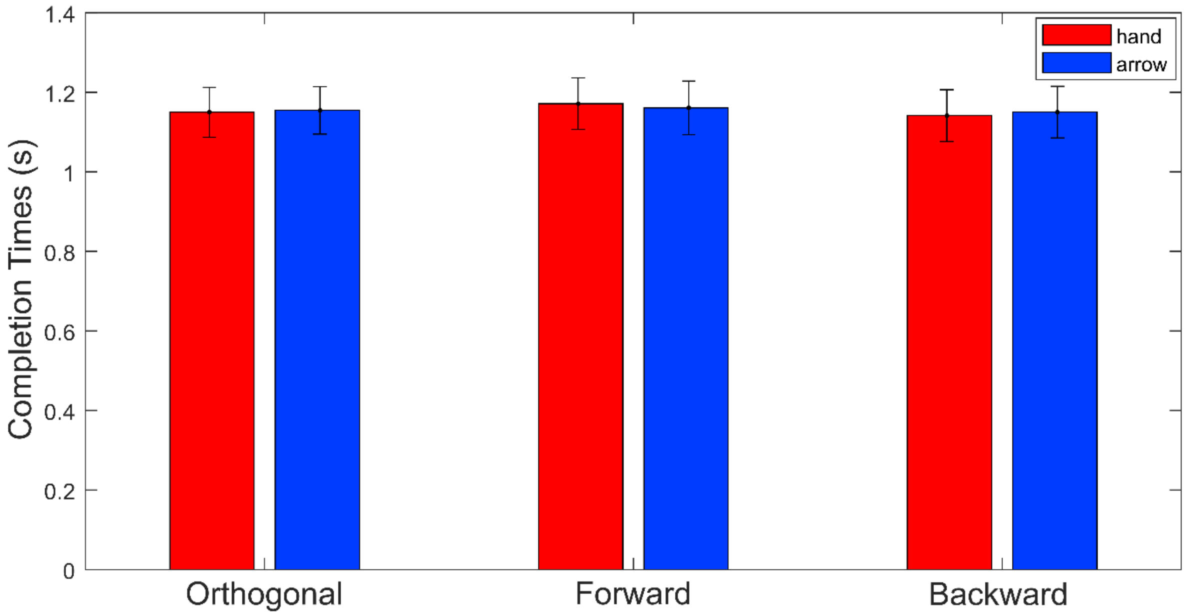

Figure 2.4.2 shows the completion times in seconds for movements relative to cursor orientation and target location. Error bars show standard error.

To explore the effect of target location, a 2x3 (2 cursor images, 3 relative target locations to cursor orientation: orthogonal, forward and backward) repeated measures ANOVA was performed in Matlab (Trujillo-Ortiz, 2021a) and revealed a main effect of relative target location (F(2,38) = 3.81 p = .031). Post hoc tests revealed that there was a significant difference between forward movements (in the direction of the cursor point) and backwards movements (t(19) = 3.00, p = .007). Backwards movements had significantly faster completion times than forward movements.

There was no main effect of cursor image (F(1,19) = 0.02, p = .892) and no interaction.

2.4.2 Path deviation from straight at the midway point

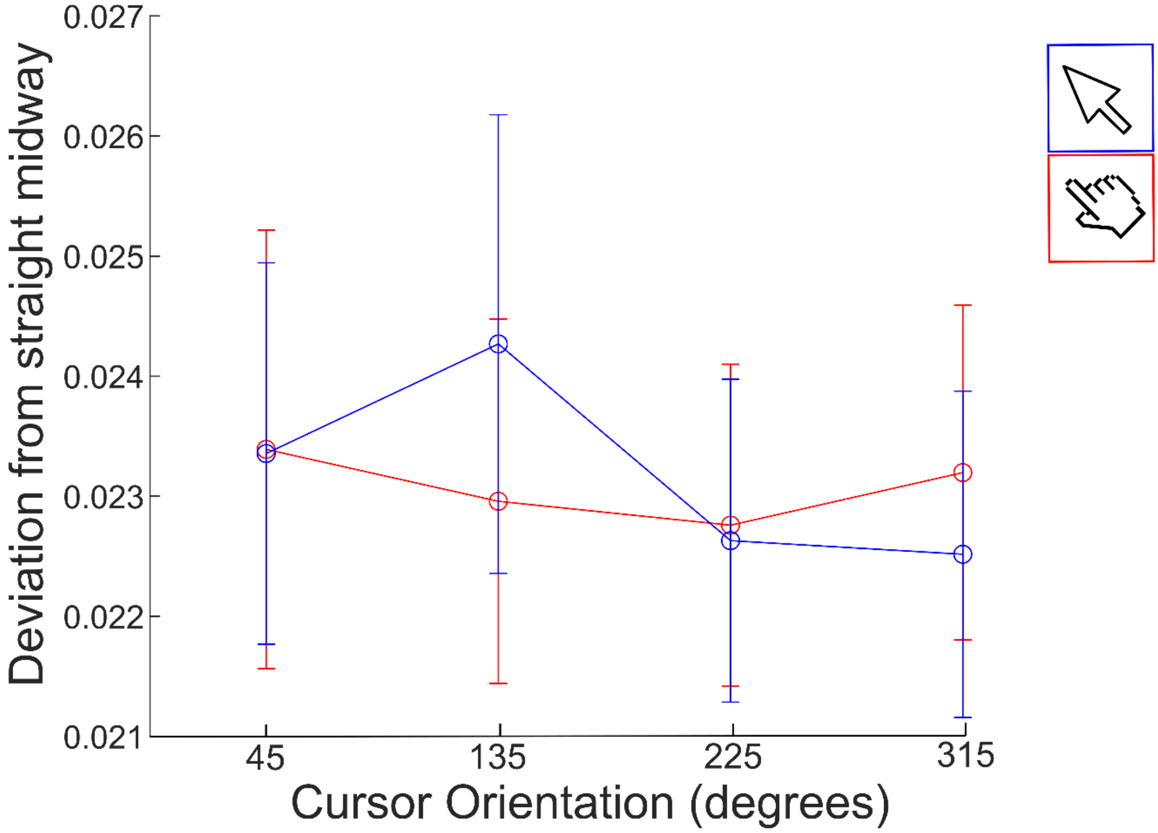

Figure 2.4.3 shows deviations from a straight path at the midway point of the movement, for hand and arrow cursors for the four orientations, in arbitrary units. Error bars show standard errors.

We further looked at task performance in relation to the efficiency of the movements. The path the cursor takes from the starting position will be longer the more it deviates from a straight line. The deviations could be caused by biological constraints in moving the mouse in certain directions or could be an indicator of a movement that is not initially on target and is then corrected.

The deviation of the mouse cursor path from a straight line at the midway point was analysed using a three-way 2x4x8 (2 cursor images, 4 cursor orientations and 8 target locations) repeated measures ANOVA in Matlab (Trujillo-Ortiz, 2021b). This revealed a main effect of target location ($F(7,133) = 7.77$, $p < .001$), an interaction between cursor orientation and target location ($F(21,399) = 2.23$ $p = .002$), and a three-way interaction between cursor image, cursor orientation, and target location ($F(21,399) = 1.87$, $p = .01$). The deviation from straight was more affected by the cursor orientation for the arrow cursor.

There were no main effects of image ($F(1,19) = 0.02$ $p = .884$) or orientation ($F(3,57) = 0.55$, $p = .654$) and no other interactions.

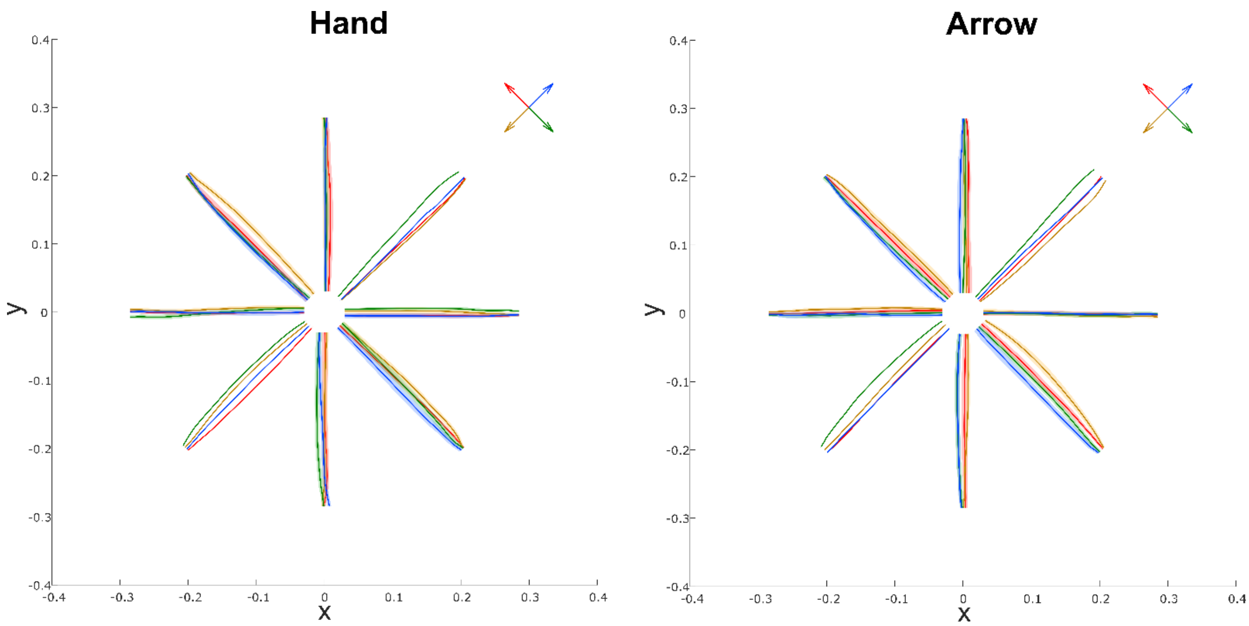

Figure 2.4.4 shows the average path taken to targets. The points represent target locations, different colours are for different cursor rotations. The shaded areas show the standard error.

There was more of an increase for target paths at 90° angles from cursor orientation, shown by an increased curvature of the lines in the figure 2.4.4. From the figure, we can also see that there is possibly more of a path diversion for the green and yellow lines (135° and 315° cursor rotation respectively), which are the least plausible rotations when considering the biological limitations of the physical hand. The deviation is more pronounced for the arrow cursor. Looking at the most curved lines, it appears that participants curved around the target to approach from the point of the cursor.

The significant interactions involving the target location were then explored considering their location relative to the direction of the cursor, as we were not interested in the absolute target location which could be affected by biological constraints.

<u>2.4.3 Deviation from straight to target relative to orientation and target location</u>

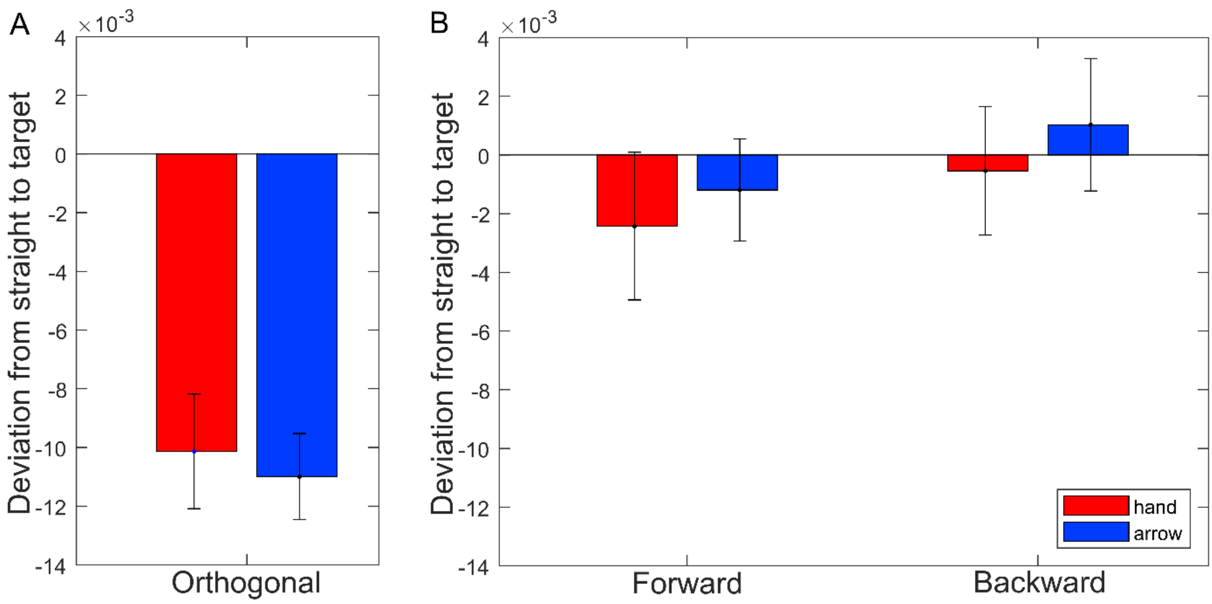

Figure 2.4.5 shows the path deviation from a straight line in arbitrary units. Part A shows the deviation when the targets are orthogonal to the cursor pointing direction. More negative values represent a deviation opposite to the cursor pointing direction (away from the cursor point). Part B shows the deviation for target locations that are forward along the target path and backwards along the target path relative to the cursor pointing direction, negative values represent a counterclockwise bias. Error bars show standard error.

The curvature of the cursor path, specifically the deviation of the path from a straight line considering the cursor orientation relative the target location, was considered. Deviations were calculated based on the average path per participant and taken at the midway point.

A 2x3 (2 cursor images, 3 relative target locations to cursor orientation: orthogonal, forward and backward) repeated measures ANOVA was performed in Matlab (Trujillo-Ortiz, 2021a) and revealed a main effect of relative target location ($F(2,38) = 16.77$ $p < .001$). Post hoc tests revealed that there was a significant difference between movements that were orthogonal to cursor orientation and both forward and backwards movements ($t(19) = -4.06$, $p <.001$ and $t(19) = -4.74$, $p <.001$ respectively). There was no difference in curvature of the path for cursors travelling forward or backwards ($t(19) = -1.47$, $p = 0.16$).

Participants moved the cursor in more of a curve to reach targets that were orthogonal to the cursor direction, in comparison to targets that were in line with the cursor direction, so that the point would have to be moved either forwards or backwards to reach the target. There was no main effect of cursor image ($F(1,19) = 0.24$, $p = .62$).

2.4.4 Agency

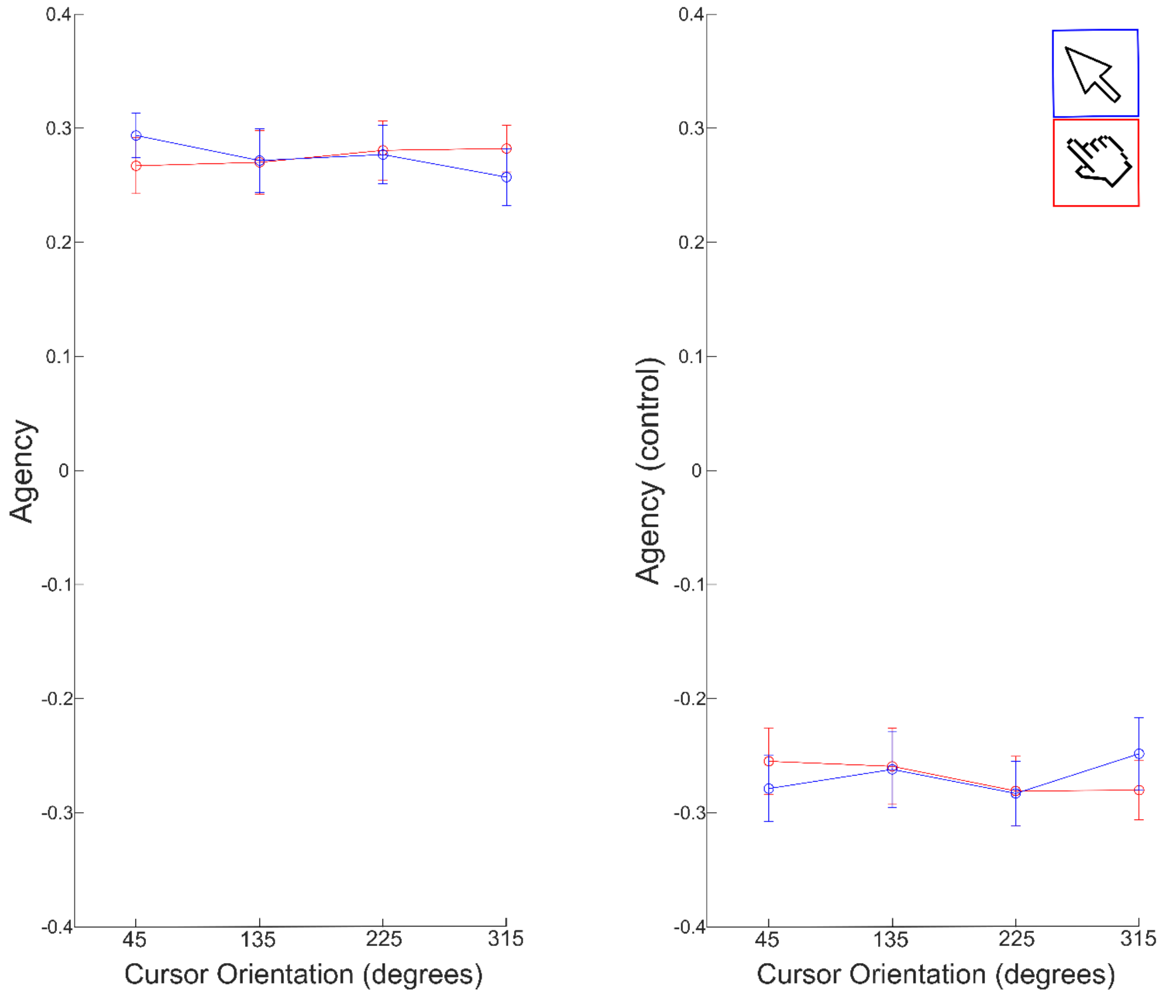

Figure 2.4.6 shows the rating for the agency statement and the agency control statement for the hand and arrow cursors, averaged for each cursor orientation. The rating bar goes from -0.4 “Not at all” to 0.4 “Very much” as this was the screen position of the rating bar in a.u. Error bars show standard error.

After each trial, participants were asked to rate their subjective feelings of agency and familiarity over the cursor movements.

The first rating statement was “I felt I was controlling the cursor”. The arrow shaped cursor at 45° rotation was predicted to produce the highest ratings of agency for the movements. We also predicted that hand shaped cursors at biologically incongruent positions may reduce the sense of agency.

A two-way repeated measures ANOVA (two cursor images, four orientations) was performed in Matlab (Trujillo-Ortiz, 2021a) to compare the effects of these variables on the amount of agency the participants felt over the cursor movements. This revealed that there was a significant interaction between cursor image and cursor orientation ($F(3,45) = 3.861$ $p = .0153$).

Figure 2.4.6 shows that participants felt more agency towards the arrow cursor pointing to the familiar top left (45°) whereas the hand cursor stayed mostly level. Post hoc tests revealed that there was a significant difference between the arrow cursor at 45° and 315° ($t(15) = 2.86$ $p = .012$), but there was no difference between any orientations for the hand cursor and no other combinations of cursor image or rotation were significantly different from each other.

There was no main effect of image ($F(1,15) = 0.001$, $p = .981$) and no main effect of orientation ($F(3,45) = 0.65$, $p = .587$).

2.4.5 Agency control

There were no main effects found for image ($F(1,15) = 0.01$, $p = .922$) or orientation ($F(3,45) = 1.22$, $p = .314$) for the second rating statement “The cursor seemed to have a will of its own”. There were also no interactions. Participants were expected to give the reverse ratings to the previous question and since the cursor was always under the control of the participant, this result was expected.

2.4.6 Familiarity

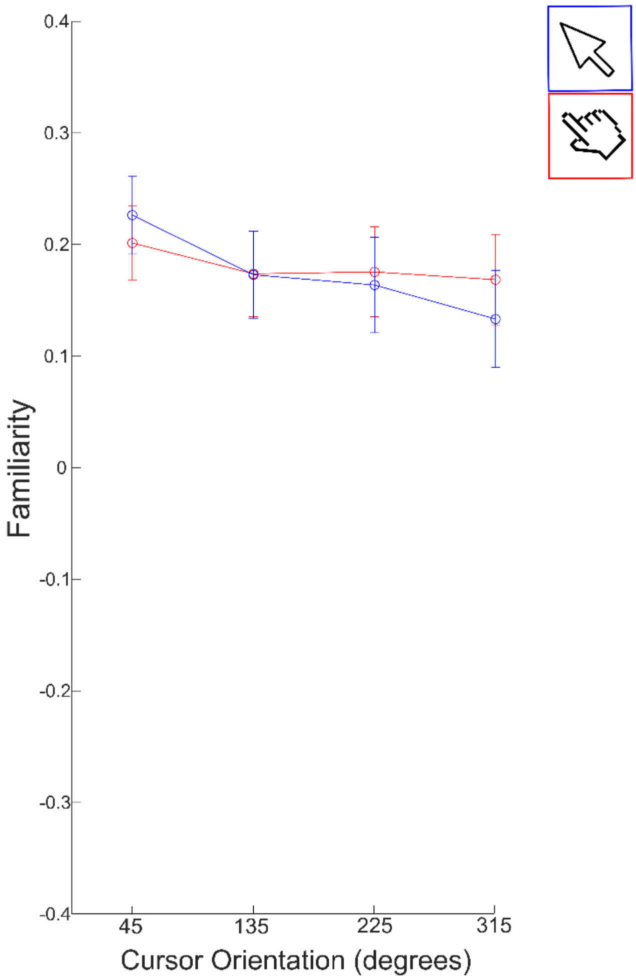

Figure 2.4.7 shows the rating for the familiarity statement for the hand and arrow cursors, averaged for each cursor orientation. The rating bar goes from -0.4 “Not at all” to 0.4 “Very much” as this was the screen position of the rating bar in a.u. Error bars show standard error.

The third rating statement was “The cursor felt natural to me”.

A two-way repeated measures ANOVA (two cursor images, four orientations) was performed in Matlab (Trujillo-Ortiz, 2021a) to compare the effects of these variables on how natural the cursor felt to the participant. This revealed that there is a main effect of cursor orientation ($F(3,45) = 4.25$; $p = .01$) and an interaction between cursor image and orientation ($F(3,45) = 3.30$: $p = .0286$). There was no main effect of cursor image ($F(1,15) = 0.36$, $p = .559$) meaning that the hand cursor was not rated as feeling less natural overall than the arrow shaped cursor.

Perceived naturalness for the arrow cursor was highest with the cursor pointing at 45°, significantly higher than 135° ($t(15) = 2.21$ $p = 0.04$), 225° ($t(15) = 2.60$; $p = 0.02$) and 315° ($t(15) = 3.50$; $p = 0.003$).

There was no difference in perceived naturalness with different orientations when considering just the hand shaped cursor.

In summary, fastest completion times were found at familiar cursor rotations (45°). There was more deviation from a straight path to targets orthogonal to cursor orientation for both cursors, with the arrow cursor being more affected by orientation. Participants felt the most agency towards the arrow cursor pointing to the familiar top left (45°). The level of familiarity of the arrow cursor is significantly affected by orientation, but this is not the case for the hand cursor.

2.5 Discussion

The computer mouse as a tool to interact with the virtual world is vitally important for many everyday tasks. Being able to quickly and accurately select the intended areas of the computer screen allows us to effectively carry out our jobs, fill out online forms, and interact with people all over the world. The performance of virtual tasks is affected by the sense of agency (D'Angelo et al., 2018) and by the familiarity with the tool, possibly due to an expansion of the PPS (Biggio et al., 2020).

The current study aimed to find out whether the familiarity of a mouse cursor affects participant behaviour and their perception of how in-control they were of the cursor during an on-screen target pointing task, with cursors visually presented as the standard arrow-shaped cursor or as a hand-shaped cursor and presented at different orientations.

We expected that the best performance and highest agency ratings would be found for the arrow cursor at the most familiar orientation (pointing towards the top-left). The worst performance and agency ratings were expected for cursor orientations that were not biologically congruent, i.e., pointing towards the participant.

The results show that even in a simple pointing task, cursor appearance and familiarity do affect both pointing behaviour and the feeling of agency.

The change in stimulus orientation and appearance should not have made the task objectively harder, as participants had the same level of control throughout the task. This was to ensure that any differences could be attributed to how the cursor felt subjectively and/or how the cursor was represented in the brain.

As predicted, trial completion times were significantly faster for cursors pointing to the familiar top left, however this was true for both the arrow and the hand shaped cursor. This suggests that the familiarity with the orientation of the cursor aided in task performance, allowing participants to more quickly plan and execute the motor movement, and was not affected by the image. This could be because the tool matched the ingrained internal model that the participants had for the mouse cursor, specifically the expected position of the 'hotspot'.

It was also suggested that the hand cursor would have more tolerance to unfamiliar changes, if they were anatomically congruent. For example, pointing to the top right is not familiar for cursor use but is a position that the real hand can move into comfortably and we would be familiar with seeing the hand in that position, compared to cursors pointing to the bottom right as it is more difficult to position the real hand to point that way comfortably, and would therefore not be a familiar way to see or use the hand. This was not supported by the completion times, which did not significantly differ between the hand and arrow cursor.

When the cursor starting orientation is pointing at the target location, there could be a pre-cuing effect, which reduces reaction time (Hertzum & HornBaek, 2012) and therefore could reduce target completion time. The results do not support this as backwards movements had faster completion times. It could be that participants are quickly moving the cursor to the target area before adjusting to approach the target from the point of the arrow, rather than planning the whole path from the beginning of the movement, which could take longer, but would need further investigation.

There is an assumption when using a mouse that the hotspot, the active part that registers where a click happens, is in a certain place. When this is not the case, participants would have to make adjustments to overcome entrenched habits (Chong, Kee, & Chaturvedi, 2015) meaning that they would need more time to plan the movement or make an adjustment mid-movement i.e. not approaching the target in a straight line. The hotspot was always at the point of the cursor, but the point varied in its position within the cursor image.

The curvature of the path is therefore another indicator of task performance. The path the cursor takes from the starting position will be longer the more it deviates from a straight line. The deviations can be caused by biological constraints in moving the mouse in certain directions or could be an indicator of a movement that is not initially on target and is then corrected.

There was a clear interaction between the cursor orientation and target locations for the deviation of the cursor path from a straight line, as shown in figure 2.4.4. These can be summarised as showing that paths were longer for targets that were at 90 degrees to the cursor orientation. One possible interpretation of this effect is that it is easier to plan movements along the cursor's axis, rather than against it, where participants might attempt to curve around to approach the target from the tip of the cursor. This would make more sense for a physical finger, where it is important to approach an object from a certain angle to be able to grasp the object without colliding with it (see for example Brenner & Smeets, 1995; Smeets & Brenner, 1999) but it is interesting that this effect translates to a virtual finger, or cursor. Differences in path deviation were more pronounced for rotations that were unfamiliar, but only when using the more familiar arrow shaped cursor.

Larger effects for oblique target locations can be linked to the oblique effect. Yousif and McDougle (2023) propose that this effect is due to "deficits in angular acuity in the oblique regions of space" causing people to be worse at pointing tasks and making orientation judgements further away from the cardinal axes. There could also be a biological effect, but since this experiment was performed remotely, we would be unable to draw conclusions about the direction and amplitude of the physical mouse movements. It could be possible that, since tasks performed with the physical hand would be constrained by the biological ability of the hand and arm; movements that are achievable in the virtual environment may have felt less natural and adjustments to those movements could have been made to reduce this discomfort or to continue learned behaviour.

Another measure of deviation that we assessed was the deviation from a straight line considering the relative position of the targets to the cursor orientation. We found that there was a main effect of target location relative to the cursor orientation, and that movements that were orthogonal to the cursor orientation were significantly more curved than both forward and backwards movements.

Due to the shape of the cursors, non-congruent trials (where the hotspot is not pointing towards the target at the start of the trial) could mean that the target is obscured by the tail of the image when approaching it in a straight line. This could have influenced the increase in path deviation as participants are curving the movement path so that the point of the cursor approached the target first. Since there was no difference in curvature for forward trials versus backwards trials, it suggests that this is not the case, and is more likely that planning the cursor movement along its axis is easier regardless of the point location. The cursors used were transparent, with only the outline being opaque, which would have reduced the likelihood of the cursor fully obscuring the target.

The results from the subjective rating scales showed that participants felt the most agency when using the arrow cursor pointing to the familiar top left (45°). The reported feelings of agency for the hand cursor were only rated as being lower than the arrow cursor when both cursors were at the familiar 45°, otherwise there was no difference between them. The level of agency was therefore not affected by the cursor image when the rotation was already unfamiliar.

It should be noted, however, that the ratings were always quite high, which was expected as participants always had the same level of control. There was no change to the input, meaning that the visual feedback of the cursor associated with the mouse movements was as expected, which has been reasoned to preserve the sense of agency (Gozli & Brown, 2011). During movements, we rarely notice the sensory feedback from our actions or the minor adjustments we make while pursuing goals, we just know that we are successfully having an effect on our environment (Frith, 2005). Participants would know that they successfully clicked the target and would not be aware of the internal movement planning adjustments happening to account for the rotated image.

Cursors at 45° also had best completion time. It has been found that people attribute more agency to an action when the performance score is inflated (Wen, Yamashita, & Asama, 2015b); agency was attributed after the fact. Although the performance did not differ between the cursor images, participants felt that they had more control with the more familiar arrow shaped cursor. It is possible that the increased agency (and expansion of the PPS) made the task completion easier, but we would expect therefore that participants would perform better with the arrow cursor that was rated higher for agency, when completion times were actually the same for both the hand and the arrow cursor. The unfamiliar image may have already decreased the feeling of agency to a point where the difference in orientation did not have an effect, suggesting that it was the unfamiliarity affecting the rating of agency, and not task performance. The shape of the hand image may have also affected this, as there is less of a clear point to the end of the hand cursor, as fingers have a curved tip that is much broader than an arrow point, possibly making it feel bulkier and harder to use.

Since the sense of agency was measured with explicit ratings after each set of 8 trials, the reports may have been confounded by expectations of what the task is trying to accomplish and prior beliefs about what they should be feeling, given the changes in the experiment (Gawronski, LeBel, & Peters, 2007). We have linked these reports to objective measures of task performance, but we must be cautious when drawing conclusions from explicit judgments. This effect of participant expectations may help to explain why we found no significant task performance difference between cursor images, while there was a significant difference in the level of control that participants reported that they felt.

The effect of priming has been known to increase the judgment of agency (Aarts, Custers, & Wegner, 2004), therefore, if participants registered the arrow pointing direction as a prime for target location, forward movements may have given higher agency ratings. However, in this experimental setup agency judgements were only collected after a block with different orientation and target location combinations, so we were only able to measure the behavioural effects of priming and not how this may have felt.

For familiarity, and how natural the cursor felt, there was a main effect of cursor orientation and an interaction between the cursor image and orientation. Post hoc tests showed that for the level of familiarity for the arrow cursor is significantly affected by orientation, but this is not the case for the hand cursor. Unsurprisingly, the most natural cursor was reported as the arrow cursor at 45°.

The level of naturalness for the hand cursor may not have changed for the different rotations because the image of the hand was already unfamiliar, participants were not used to having a hand representation on their screens. If we consider the cursor as a representation of the real hand, it is possible to imagine that a higher level of embodiment would be felt for the hand shaped cursor as it is more similar to the real hand. However, this simplistic representation may not have been close enough in likeness to the real hand to increase familiarity. This could also suggest that familiarity is domain or task specific. It would be interesting to perform this experiment with participants who do not regularly use a computer, as they would have no prior familiarity to a cursor that is not similar to their real hand. The number of people who have not used a computer mouse and cursor was dwindling but with the increasing use of touch screen devices, this may again be viable.

Computer users tend to dislike updated versions of applications, such as a change in the layout of a user interface (UI, see Vaniea, Rader, & Wash, 2014, who also found that updating with a poor UI can dissuade users from installing future necessary security updates). Even if a cursor of a different shape or orientation was found to be more accurate or easier to use, there may be limited uptake. There would need to be strong evidence of increased performance to persuade software companies to risk losing customers. The increase of touch-screen use means that this may be less relevant more widely regarding UI use.

There is also an argument that designing tools to look more natural may not be optimal, as increased familiarity seems to be domain specific, people are more used to seeing a hand or finger pointing generally, but more often see and use an arrow on-screen. Designing tools prosthetics for specific uses may then also benefit from being optimally shaped for utility rather than imitating the natural shape, and further research on the length of time needed to induce the domain specific familiarity, or minimum training time needed to use the tool optimally would be necessary.

Inferences about the positioning of the participants' hands are limited by the fact that this experiment was carried out remotely through an online platform. People sit at different positions in front of their PCs with varying mouse positions; for example, if the mouse is positioned more to the side, the hand position could have an angle more consistent with the 315° cursor (top right), which is why it was expected that more natural ratings for that orientation would be given by some participants. This was not supported by the results, however. Further experiments would hopefully take place in-person so that positioning could be the same across participants, perhaps inviting them to indicate their regular setup by dragging a keyboard and mouse on a schematic to assess familiarity with the experimental setup. This could also be done with an online experiment, so although the setup would not be standardised, we would have an indication of how participants are positioned during the task.

The pre-experiment questionnaire captured system information and information about how participants generally used a mouse, however there is no way to guarantee the accuracy of self-report. Again, an in-person setup would be optimal.

Mouse sensitivity can be changed in certain applications. Although the experiment did not change mouse sensitivity, if a participant is used to using the mouse with an application at a different sensitivity as their primary computer use, this may have affected their feeling of familiarity and possibly their task accuracy.

The arrow cursor had stronger effects relating to subjective ratings at different rotations. This shape will be explored further in the next chapter, by varying the size alongside the rotation as an alternative way to reduce the feeling of familiarity. Since the bulkier shape of the hand cursor may have also affected the task performance, the increased size of the arrow cursor may clarify if this had an effect.

Chapter 3: The effect of cursor size and orientation on pointing behaviour and the sense of agency

3.0 Abstract

The sense of agency is the feeling of authorship over our own actions. This can extend to tool use, including the feeling that we are in control of a virtual tool, such as a computer mouse cursor. In a previous study we found that the shape and orientation of the cursor affected perceived familiarity/agency of using the cursor as well as the movement paths in a target pointing task. This study builds on those findings by looking at the effect of cursor size. Participants performed a target-pointing task, whereby they clicked on targets at 8 different locations as quickly and accurately as possible. The cursor was represented as an arrow, similar to a regular computer cursor, either small (close to normal size) or large (increased by 200%), and was presented in varying orientations (45°, 135°, 225°, and 315°). Per set of 8 trials, blocked for cursor size and orientation, participants answered questions on the level of agency felt and the perceived naturalness of the cursor. The feelings of agency and naturalness were higher overall for the small cursor and was strongest for the small cursor in the most familiar orientation (cursor pointing top-left for righthanders). Completion times were also significantly faster with the cursor pointing top-left, with the larger cursor having longer completion times for movements that were backwards along the path to the target. Movement paths were curved in cases where the pointing direction was orthogonal to the cursor orientation. These curvatures were more pronounced for large cursors. These results support our previous findings and show that cursor size affects both pointing behaviour and the feeling of agency.

3.1 Introduction

In the previous chapter, the sense of agency, i.e. the sense of authorship over our own actions (Ismail & Shimada, 2016) and the feeling of familiarity towards mouse cursor movements were introduced. The cursor image and orientation were varied to see if target pointing behaviour and feelings of agency and familiarity were affected. The arrow shaped cursor was found to have stronger affects relating to subjective ratings at different rotations. This chapter will focus on the size and orientation of the mouse cursor in the same pointing task to see what effect they have on task performance and the subjective feelings of agency and familiarity.

Being online is important for everyday life and social interaction. While this facilitates interactions for everybody, for some people it allows them to access a world that they may otherwise be unable to, perhaps due to disability, or situations where physical movement between places is restricted such as during the pandemic. This gives people access to education, social spaces and work opportunities that they would not otherwise have.

In order to access this, users must be able to effectively perform the task they intended, such as selecting the correct menu options in a screen or pointing at the right target in a video game, which is facilitated by a User Interface (UI). When considering UIs, it is important to ensure that they are intuitive and accessible. Both usefulness and ease of use are necessary for user acceptance of an interface (Davis, 1989).

Mouse cursors are a valuable tool as there needs to be a representation of real-world movements made by the user, providing a viable indicator of what is going to be selected on the screen (Dix et al. 1998). A user could otherwise tab through icons that are highlighted but this reduces the degrees of freedom. Marken (1991) suggested that the degrees of freedom when moving a mouse over a two-dimensional surface is only limited biologically by the muscle fibres used to control the mouse and their possible movements. Being able to move freely also means that users can navigate between distant options on a screen with ease. This opens up possibilities such as in gaming, with mouse-based movements often used for target acquisition (Looser, Cockburn & Savage, 2005) and computer-based learning environments such as those described in Jones and Okey (1995).

Stimulus response compatibility in this case refers to the compatibility of the mapping between the spatial characteristics of a visual stimulus, and the corresponding motor movement (Fitts & Seeger, 1953; Po, Fisher & Booth, 2005). Put more simply, the appearance of a virtual tool affects how it is used. Increased compatibility has been found to increase performance. Therefore, the orientation of the cursor needs to be considered when designing optimal UIs. For example, if menu options are more to the left-hand side of the screen, the cursor pointing to the left makes sense to aid in selecting the correct option, as the cursor is likely to be approaching from a rightwards location. Options on the right of the screen may be better served by a cursor pointing to the right. The typical mouse cursor is in the form of an arrow pointing to the top left of the screen (Po, Fisher, & Booth, 2005). UIs are likely designed to accommodate the left pointing mouse, as this is the most typically used, but this may not be optimal.

There are various explanations offered as to why it is the case that we predominantly use the top-left pointing cursor. Originally the mouse cursor was an arrow pointing up (as shown in Reimer, 2005) but was then changed to the tilted arrow due to the low screen resolutions of early computers: one straight line and one line at a 45° angle is much easier to draw and recognise when you are only able to represent an arrow with large square pixels (as shown in Lyon, 1981).

Another explanation relates to the lack of processing power in early computers. By having the click position (or hotspot) in the top left corner of the bitmap it made it easier to calculate the click location, as the cursor's bitmap origin is also the top left, which is the default on Windows machines (Microsoft Developer Network, 2008).

Although these are very reasonable explanations for the original cursor designs, they don't address why we have kept the top-left pointing cursor now that we have moved way beyond the limitations of early computers. If we still use this shaped cursor due to simple nostalgia or inertia, changing the orientation of the cursor should not affect ease of use beyond familiarity.

One alternative explanation refers to low level visual cognition, where the primary visual cortex processes simple features from received visual information such as lightness, size and orientation (Ware, 2010). We are able to tune to particular orientations of lines in order to pick them out more quickly against lines and patterns of differing orientations, particularly at oblique angles, this is known as the popout effect (Treisman & Gormican, 1988). Most graphics, blocks of text, spreadsheets and so on, will contain vertical and horizontal lines, making the tilted cursor easier to spot and follow. This could be part of a subset of stimulus-response compatibility known as figure-ground relations as coined by Fitts (1951, see also Kantowitz, Triggs, & Barnes, 1990 for further information) where it is hard to distinguish the cursor (or figure) from the background information on the screen (ground), especially when there are other moving elements and it is unclear from the user's perspective whether their physical inputs are moving the information or the indicator.

Early developers of the mouse cursor also felt that top-left was the most intuitive orientation for the cursor, given the usual positioning of the mouse relative to the screen (Po, Fisher & Booth, 2005). The cursor is shaped naturally as if you were to point your right hand at the screen, if you had one moderately sized screen and were sitting centrally in an ergonomically suitable position (as detailed in an article by Muller, 2021). The smaller tip of the arrow mimics the perspective of a finger pointing away from the body towards a vanishing point.

Another reason could be simple familiarity, we are used to seeing the cursor pointing to the top left. In the previous chapter, it was shown that the cursor pointing to the top left felt more natural. According to Fitts (1954, p.268) “movements of differing amplitude but of equal difficulty in terms of information tend to be of approximately equal duration” meaning that the trial completion time should not have changed unless the orientation change provided more information that needed to be processed.

Fitts (1954) proposed a law on motor movement that predicts the efficiency of pointing techniques, with the time taken to select a target being determined by its distance and size (Looser, Cockburn & Savage, 2005). This calculation has often been used to develop effective UIs, and there have been many studies that look at this (for a review see Jiang & Gu, 2020). Fewer studies have considered the size of the pointing device when considering optimal pointing performance. An inverted Fitts’ paradigm is when the pointing device, such as the peg, is larger than the target, thus increasing the effective size of the target and making the task easier (Hoffman & Sheikh, 1991).

There have been some studies looking at physical pointing tasks with different sized inputs (for example see Fitts, 1954, and Drury & Hoffman, 1992). It was often assumed in these tasks that the finger was the standard width of the pointing device (Hoffman and Sheikh, 1991), as finger size is naturally fixed once a person reaches adulthood, but this would not be the case for tool use or in virtual environments. Also, for these tasks the entire pointing device would have been the effective area, or ‘hotspot’. Worden and colleagues (1997) used an area cursor and found that there was increased performance in line with Fitts’ law when using a cursor that is broader than the target. However, this would not apply to the most commonly used cursor which has a single hotspot at the vertex of the arrow point that can be used to interact with the display (Dix et al., 1998).

For a satisfying experience, users must feel as though they are in control of the cursor, which means being able to accurately make desired selections. While there may be an element of personal preference in cursor design, the role of familiarity and compatibility with the UI design need to be taken into account, and task performance should be linked to how people feel when they use the cursor. Previous studies have either not taken into consideration the changing of cursor size, or have not asked participants whether the cursor felt natural to them, and to what degree they felt in control.

The aim of the present study is to investigate how familiarity with the size and orientation of the tool (in this case a mouse cursor) affects behaviour and the feeling of agency, without changing the responsive behaviour of the tool. To do this we used the same paradigm as used in the previous chapter. Participants completed a target-pointing task on a computer screen, with cursors that vary in size (arrow shaped cursors at 0.1 a.u. and 0.2 a.u.) and orientation (45°, 135°, 225°, and 315°). Participants could move the cursor to click targets at 8 different locations as quickly and accurately as possible and then answered questions relating to agency and familiarity on a sliding scale.

We expect to find that the smaller cursor at 45° rotation (pointing towards the top left of the screen) has the best task performance as it is the most familiar to the participants. It therefore should also produce the highest ratings of agency over the movement.

Since the larger cursor is less familiar and takes up more screen space, we would expect that the orientation would have less effect on feelings of agency and familiarity, as these would already be diminished. We would also expect that task performance would be worse for targets that the cursor has to move backwards to along its axis, as it is bulkier and could obscure the target location (although it is transparent, the black lines may obstruct the target enough to have an effect).

We also expect that cursors pointing in the direction of the target location would have faster trial completion times and a straighter path to the target, as the arrow direction could have a pre-cuing effect, as it is often seen to indicate an instruction to move in a certain direction (Kantowitz, Triggs, & Barnes, 1990), and could make planning the path to the target easier due to stimulus-response compatibility.

3.2 Method

This experiment used the same paradigm as described in the previous chapter, with the exception that the cursor image was the same arrow shape in both conditions, instead at different sizes. The procedure will be reiterated here for convenience.

The study was approved by the Ethics Committee of the Department of Psychology at the University of Essex prior to data collection (ethics code: ETH1920-1719). The participants were naive with respect to the purpose of the experiment and informed consent was obtained from each participant through Qualtrics.

Participants were psychology students who were recruited for course credits (N = 22, aged between 18 and 54 (M= 26.23 SD= 7.34)). Power considerations are included in Appendix A.

Participants were then redirected from the participation system to the Qualtrics survey.

3.2.1 Demographic data procedure

Through Qualtrics participants self-reported demographic information (age, gender etc). As part of this participants also self-reported which hand is their dominant hand (the options were “left”, “right” and “both the same”) and then which hand they usually use to control a computer mouse. The survey also instructed participants to use the mouse in their usual hand while completing the experiment. All participants reported that they normally used their right hand to control the mouse, however two participants reported that they were left-handed and one reported that both hands were the same in terms of dominance. It was assumed that the monitor and mouse position at the time of the experiment were optimal or familiar to the participant. This may not have been the case if the participant was using a shared space (see Wigdor et al., 2006 who discuss the effects of this).

Qualtrics furthermore gathered information about the device used, such as which browser, version, operating system, screen resolution, Flash version, and Java support. Participation using a mobile device was prevented, only allowing those using a laptop or PC to participate. Participants completed a short task to estimate their screen size and resolution (number of pixels per mm). Participants were instructed to place a credit card, which have a standard size of 85.60mm x 53.98mm, or similar card of the same dimensions, at an indicated place on the screen and told that they need to move the mouse to match the size of a rectangle to the size of the credit card. Mouse movements caused a rectangle on the screen to become larger the further away the cursor was moved from the origin point, allowing participants to accurately report the amount of screen space that was equal to a standard credit card.

After the short Qualtrics survey participants were automatically taken to the Pavlovia platform (Pavlovia.org) where the actual experiment, i.e., the pointing task, took place.

3.2.2 Stimuli

The pointing task was programmed using the experiment builder for PsychoPy[3] and its semi-automatic translation to JavaScript, i.e., PsychoJS (Peirce et al., 2019; Bridges et al., 2020). This code was uploaded to Pavlovia.org using the Experiment builder for running the experiment online.

The experiment did not use absolute coordinates in terms of cm or pixels, which is why henceforth all measures will be in arbitrary units (a.u). The experiment is set to use ‘height units’ which are relative to screen size, with the screen height being 1 a.u., meaning that for a standard widescreen (16:10 aspect ratio) the bottom left of the screen is (-0.8,-0.5) and top-right is (+0.8,+0.5) (PsychoPy, 2024). The visual stimuli were presented relative to screen size as making them fixed physical distances (i.e. the same retinal size for all participants) could mean that some targets would be presented off-screen for some monitor sizes.

Two cursor sizes were used, 0.1 a.u (height from tail to vertex, as used in the previous chapter) and 0.2 a.u. (see figure 3.2.1). The hotspots were at the vertex of both cursors. The arrow shape of the cursors was symmetrical to allow for rotation, similar to the one used by Po and colleagues (2005). The cursors were fully transparent (0% opaque) except for the outline (100% opaque), allowing participants to see items that would otherwise be obscured (such as the starting crosshair and targets). It has been found that viewing information through cursors doesn’t hinder performance (Worden et al., 1997). The cursors were presented at 45°, 135°, 225° and 315° rotations, with 45° being the familiar top left, as the experiment builder calculated these anti-clockwise. The cursor movements were mapped to the movement of the physical mouse.

Pointer acceleration is implemented on all major operating systems (Müller, 2017), meaning that if a user moves the mouse the same distance, but with different speeds, the distance the cursor on the screen travels will differ. No improved performance has been found for those using variable gain mice (Jellinek & Card, 1990) so no compensation was made for acceleration of the mouse movement.

3.2.3 Procedure

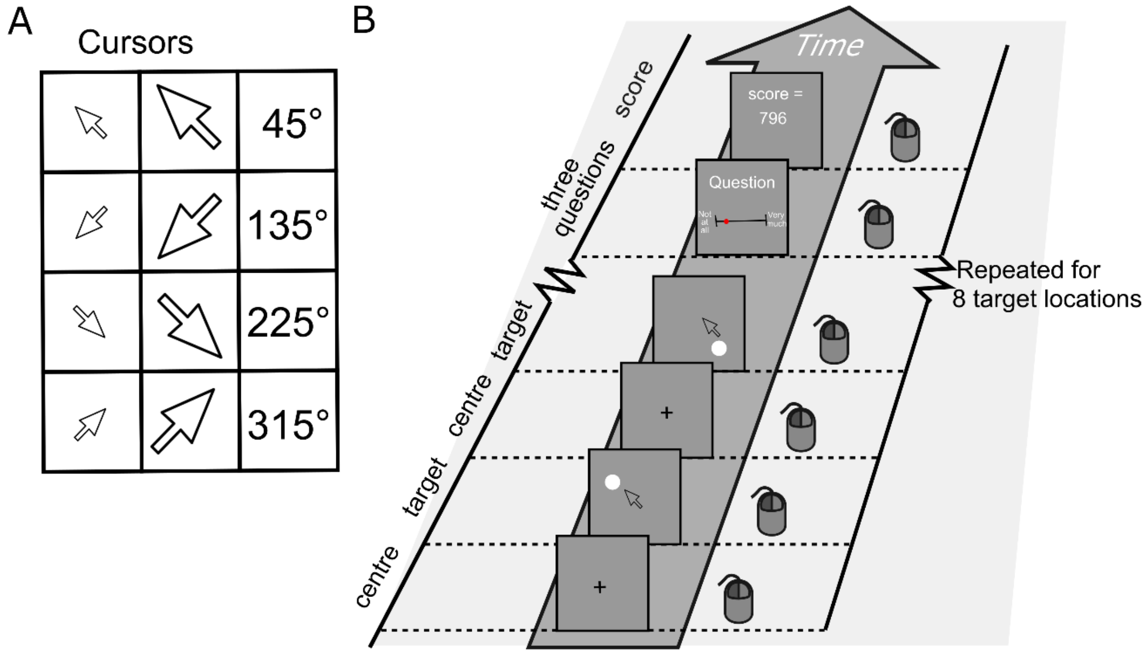

Figure 3.2.1: **A** shows the cursor sizes at height 0.1 and 0.2 a.u., and rotations used. The hotspots were at the vertex of the arrow cursor. **B** shows the procedure for each block (not to scale).

Participants were instructed to click the target (a white circle with a constant diameter of 0.05 a.u.) “as quickly and accurately as possible” using their computer mouse. Participants initiated each pointing trial by clicking a central marker (a plus ‘+’ symbol with size 0.02 a.u.). This ensured that all trials started with the cursor in the centre of the screen. Once participants had clicked the central marker, the first target for that trial was shown and the cursor size changed corresponding to the specific cursor condition for that trial (i.e. small or large cursor and its specific orientation).

The targets appeared at 8 locations spaced evenly around the central marker, (r = 0.3 a.u.) presented at 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° (cardinal and intercardinal points) in a random order.

The trials ended with a left mouse-click, even if the target was not reached. Upon left-click the target disappeared, and the central marker reappeared to start the next pointing trial.

For each trial the movements of the mouse cursor were recorded with a sample taken at every browser frame. The positions of the cursor click are also recorded.

Each block contained 8 pointing trials (one for each target location) followed by the ratings scales at the end of each block. The cursor stayed at a constant size and orientation for the whole block so that the ratings for that block would then correspond to one particular cursor type and rotation.

The feelings of agency and familiarity were measured using rating scales presented on screen. The first question targeted the level of agency the participant felt: “I felt I was controlling the cursor”. The second question is a control question relating to agency, “The cursor seemed to have a will of its own” and participants are expected to give the reverse ratings to Question 1. The third question is measuring familiarity, “The cursor felt natural to me”. The scale was presented along the x-axis, from -0.4 to 0.4 and went from “Not at all” to “Very Much” in a continuous manner. A red dot appeared on the scale and participants indicated their rating by moving the dot to the desired position using the mouse. Responses were recorded upon click.

Such on-screen rating scales have been shown to work in virtual reality (van Dam & Stephens, 2018) and are based on the questions used by Kalckert and Ehrsson (2012) to measure the sense of agency in the moving rubber hand illusion. The results from the on-screen scales have been shown to strongly correlate with results from multi-item questionnaires (van Dam and Stephens, 2018) and so they are likely measuring the same phenomenon.

After providing the ratings, participants were shown their score based on the distance from the centre of the target across 8 trials in the pointing task, with the message “Doing Well! Your score in the last block was (score)”. This completes the block. The score was shown for motivation purposes to keep the participant attempting to be as accurate as possible as well as to promote a sense of agency (Wen et al., 2015a).

To provide this score, the absolute error was calculated between the target coordinates and the click coordinates. The trial score was then calculated based on the exponential function of the negative squared absolute error, then scaled by 100 and rounded to the nearest integer. The block score was updated with each trial score, then used to display the message at the end of each block.

This procedure was repeated for both cursor sizes (small and large) and all four cursor rotations in blocks, with each block repeated a total of 5 times, to make a total of 40 blocks for the experiment. The blocks were presented in a randomised order to counterbalance and attempt to rule out any order effects.

3.3 Movement analysis

The analysis was not pre-registered.

3.3.1 Trial removal

The analysis code checked if movement trials needed to be excluded based on whether the target was reached, as well as based on other time constraints, detailed below. These triggers were only set for trial removal and did not form part of the analysis, where the whole movement path was considered.

The trigger for movement onset was set to 10% of the straight-line path length from the starting point to the target when the speed was also above threshold (a fixed value of 0.05). The movement offset was triggered when the movement path length remaining to the target was less than 20% of the straight-line distance and the speed was below the speed threshold. If onset or offset point parameters were not met, then the whole movement path was marked for removal for that trial.

Trials were removed if the participant did not click the target, or if there were fewer than five samples in the cursor path (i.e. the path was too short, which often represents a miss click). Trials were also removed if the participant waited too long to complete the movement (more than three seconds from start of trial until mouse click) or if the movement itself took too long (more than two seconds between movement onset and mouse click).

Lastly, individual trials were removed if the movement onset or completion time was more than three standard deviations away from the overall mean across all trials for that participant.

A total of 4.26% of trials were removed due to not meeting above parameters, and a further 2.05% were removed as outliers.

Participants were excluded completely if there was no data at all for any combination of: cursor identity; cursor orientation; or target location. In this case, no participants were removed from the movement analysis due to these criteria.

The ratings for a participant were removed if a t-test revealed that there was no significant difference for the answers given in the agency rating question (Q1) and the agency control question (Q2) for that participant, since this suggests that the participant was not paying attention to the questions when providing the ratings. However, the movement data were still analysed in these cases as long as they did not meet any of the other exclusion criteria. Four participants were excluded from the ratings data. None of these participants consistently rated the feeling of agency close to 0.

3.3.2 Completion time

Completion time was calculated from when the target appeared until the mouse was clicked.

3.3.3 Path deviation

In order to analyse the deviations and movement path relative to the target, the target angle was calculated and movement path data rotated to align movement towards the target with the x-axis and deviations from straight-to-target path on the y-axis. The movement trajectories were resampled taking percentage points (10%-95% in steps of 5%) along the x-axis (in rotated spatial terms). This creates a smooth path by estimating the y-coordinates at specific percentage points along the movement path, ensuring the path doesn't have abrupt changes and follows a predictable curve. The y-value at mid-point on the x-axis towards the target was taken as the deviation half-way in the movement and stored for further analysis. For calculating average trajectories, the interpolated coordinates rotated back to the original coordinate system before averaging across trials from the same condition.

3.4 Results

3.4.1 Completion times

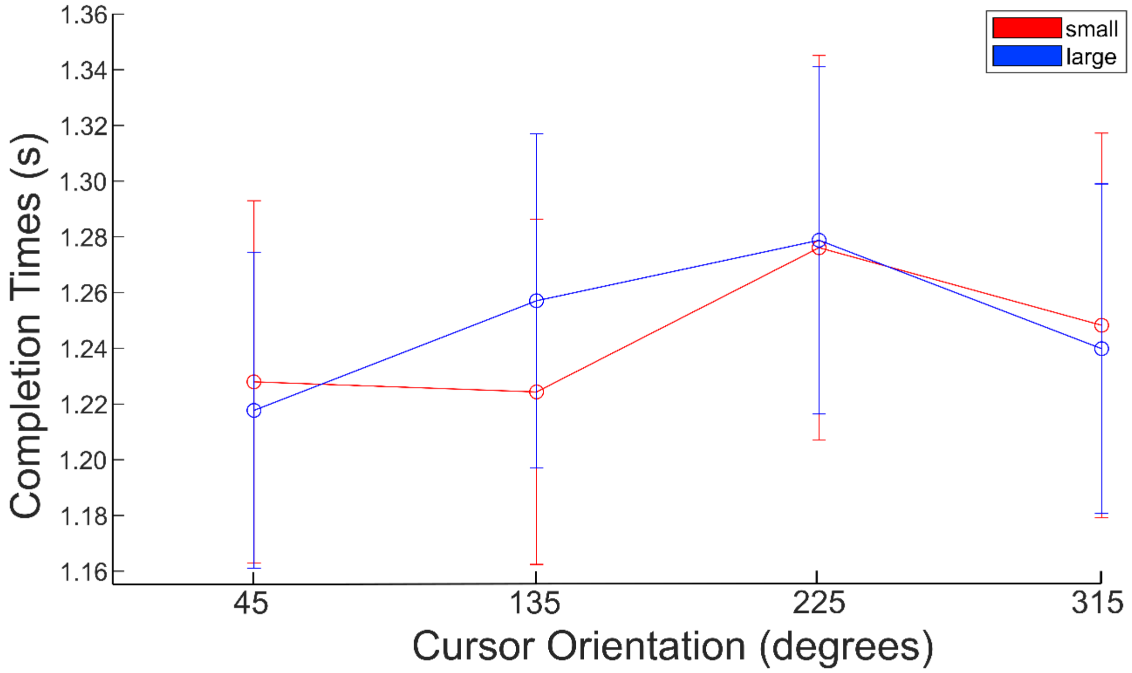

Figure 3.4.1 shows mean completion times for each cursor orientation in seconds. Error bars show the standard error.

Participants were asked to click the target as quickly as possible. Completion times were then considered to see if the different cursor sizes or orientation affected how quickly a participant could complete the task. We expected to find that the smaller cursor at 45° rotation had the best task performance as it is the most familiar to the participants.

A two-way 2x4 repeated measures ANOVA was conducted in Matlab (Trujillo-Ortiz, 2021a) to see whether cursor size (2) and cursor orientation (4) affected trial completion times. There was a main effect of cursor orientation $F(3,63) = 15.30$ $p < .001$. To investigate this further, multiple comparisons were performed. These revealed a significant difference between cursors at 45° and 135° ($t(21) = -2.23$; p =

.037), between 45° and 225° (t(21) = -6.03; p < .01) and between 45° and 315° (t(21) = -2.84; p < .01). There were also significant differences between cursors at 135° and 225° (t(21) = -4.04; p < .001) and cursors at 225° and 315° (t(21) = 4.11; p < .001). This means that participants had significantly faster trial completion times for cursors pointing to the familiar top left.

There was also an interaction between cursor size and cursor orientation (F(3,63) = 2.99, p = .03).

There was no main effect of cursor size (F(1,21) = 0.08, p = .776).

Target location was then considered, as with increased cursor size, there is increased potential for it to obscure the target when approaching from certain directions.

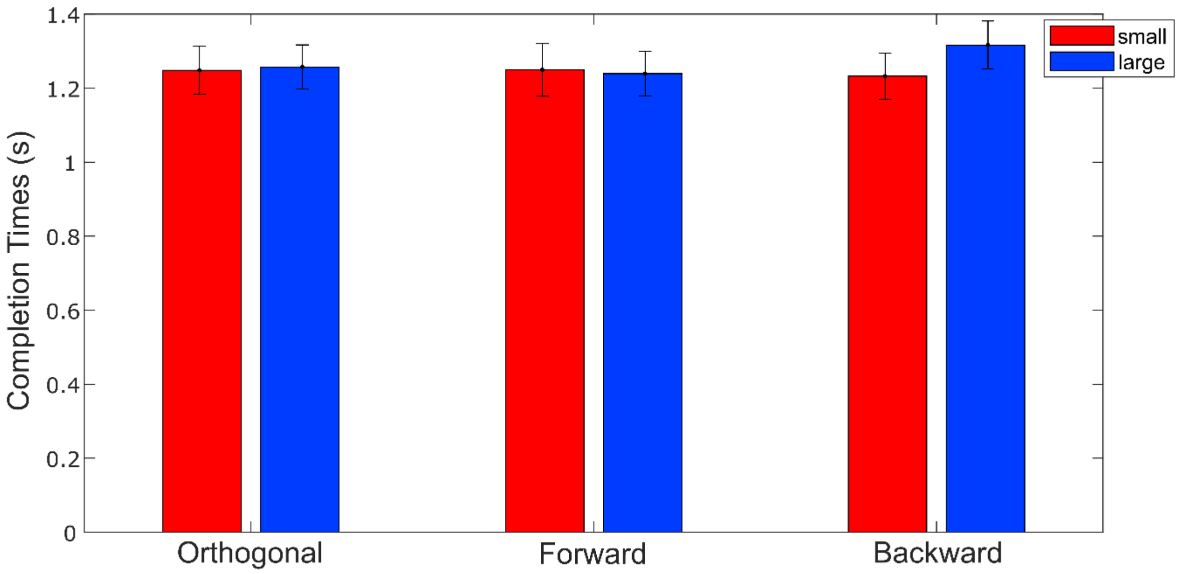

Figure 3.4.2 shows the completion times in seconds for movements relative to cursor orientation and target location. Error bars show standard error.

We also expected that cursors pointing in the direction of the target location would have faster trial completion times and that task performance would be worse for targets that the cursor had to move backwards to along its axis. To explore the effect of target location, a 2x3 (2 cursor sizes, 3 relative target locations to cursor orientation: orthogonal, forward and backward) repeated measures ANOVA was performed in Matlab (Trujillo-Ortiz, 2021a) and revealed an interaction between cursor size and relative target location ($F(2,42) = 9.34$ $p < .001$). The larger cursor had longer completion times for targets that were backwards along the movement path, significantly longer than both orthogonal movements ($t(21) = 3.67$, $p = .001$) and forward movements ($t(21) = 3.11$, $p = .005$). There was no difference between directions for the smaller cursor.

3.4.2 Path deviation from straight at the midway point

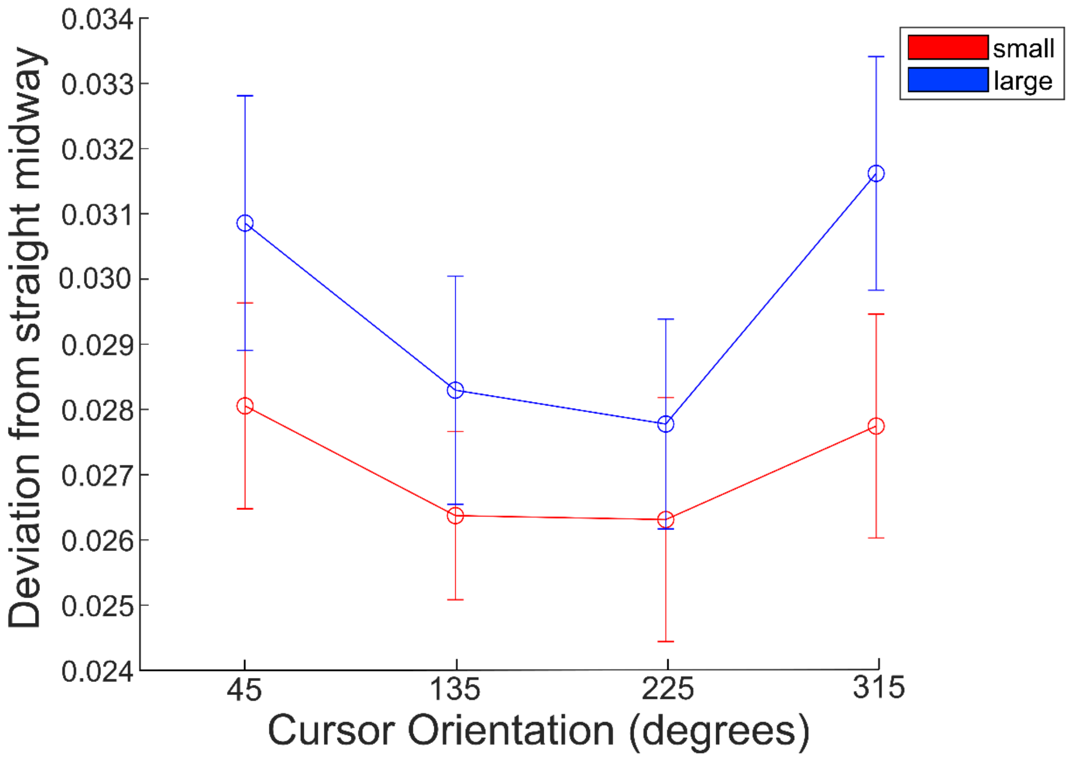

Figure 3.4.3 shows deviations from a straight path at the midway point of the movement, for small and large cursors for the four orientations, in arbitrary units. Error bars show standard errors.

We further looked at task performance in relation to the efficiency of the movements. The path the cursor takes from the starting position will be longer the more it deviates from a straight line. The deviations could be caused by biological constraints in moving the mouse in certain directions or could be an indicator of a movement that is not initially on target and is then corrected. We expected to find that the smaller cursor at 45° rotation to have the best task performance and that cursors pointing in the direction of the target location would have a straighter path to the target.

The deviation of the mouse cursor path from a straight line at the midway point was analysed using a three-way 2x4x8 (2 cursor images, 4 cursor orientations and 8 target locations) repeated measures ANOVA in Matlab (Trujillo-Ortiz, 2021b). This revealed a main effect of cursor size ($F(1,21) = 5.20$, $p = .033$), a main effect of cursor orientation ($F(3,63) = 3.28$, $p = .027$) and a main effect of target location ($F(7,147) = 9.37$, $p < .001$). There was more of a deviation for large cursors, and both cursors had more of a deviation for rotations of 45° and 315°, which are both plausible rotations when considering the biological limitations of the physical hand. There was also an interaction between cursor orientation and target location ($F(21,441) = 6.05$ $p < .001$), and a three-way interaction between cursor size, cursor orientation, and target location ($F(21,441) = 2.43$, $p < .001$). The deviation from straight was more affected by the cursor orientation for the large cursor.

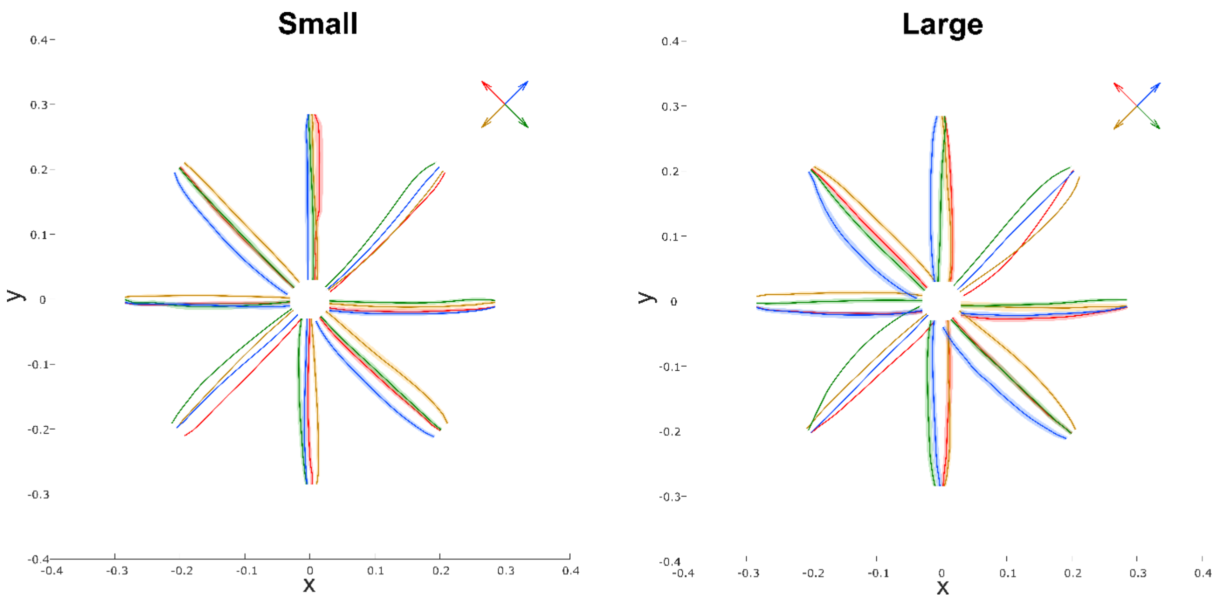

Figure 3.4.4 shows the average path taken to targets. The points represent target locations, different colours are for different cursor rotations. The shaded areas show the standard error.

There was more of an increase for target paths at 90° angles from cursor orientation, shown by an increased curvature of the lines in the figure 3.4.4. The deviation is more pronounced for the large cursor. Looking at the most curved lines, it appears that participants curved around the target to approach from the point of the cursor.

The significant interactions involving the target location were then explored considering their location relative to the direction of the cursor, as we were not interested in the absolute target location which could be affected by biological constraints.

3.4.3 Deviation from straight to target relative to orientation and target location

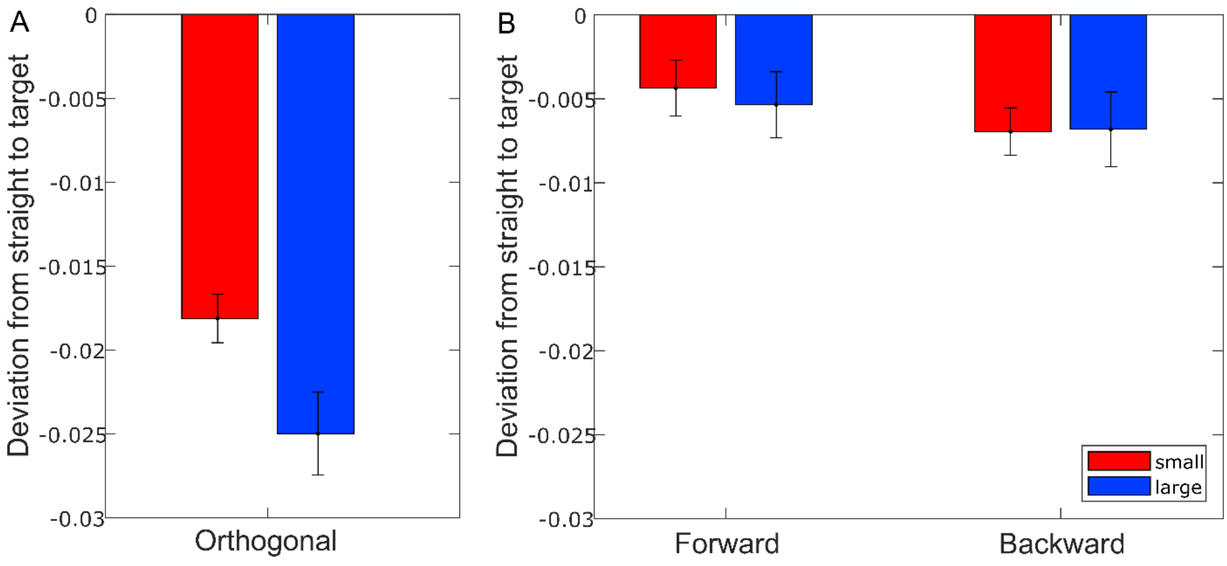

Figure 3.4.5 shows the path deviation from a straight line in arbitrary units. Part A shows the deviation when the targets are orthogonal to the cursor pointing direction. More negative values represent a deviation opposite to the cursor pointing direction (away from the cursor point). Part B shows the deviation for target locations that are forward along the target path and backwards along the target path relative to the cursor pointing direction, negative values represent a counterclockwise bias. Error bars show standard error.

The curvature of the cursor path, specifically the maximum deviation of the path from a straight line considering the cursor orientation relative the target location, was considered.

A 2x3 (2 cursor sizes, 3 relative target locations to cursor orientation: orthogonal, forward and backward) repeated measures ANOVA was performed in Matlab (Trujillo-Ortiz, 2021a) and revealed a main effect cursor size ($F(1,21) = 4.43$ $p = .048$) and a main effect of relative target location ($F(2,42) = 53.31$ $p < .001$). Post hoc tests revealed that there was a significant difference between movements that were orthogonal to cursor orientation and both forward and backwards movements ($t(21) = -8.53$, $p <.001$ and $t(21) = -8.02$, $p <.001$ respectively). There was no difference in curvature of the path for cursors travelling forward or backwards ($t(21) = 1.38$, $p = 0.18$).

Participants moved the cursor in more of a curve to reach targets that were orthogonal to the cursor direction, in comparison to targets that were in line with the cursor direction, so that the point would have to be moved either forwards or backwards to reach the target. This was more pronounced for the larger cursor.

3.4.4 Agency

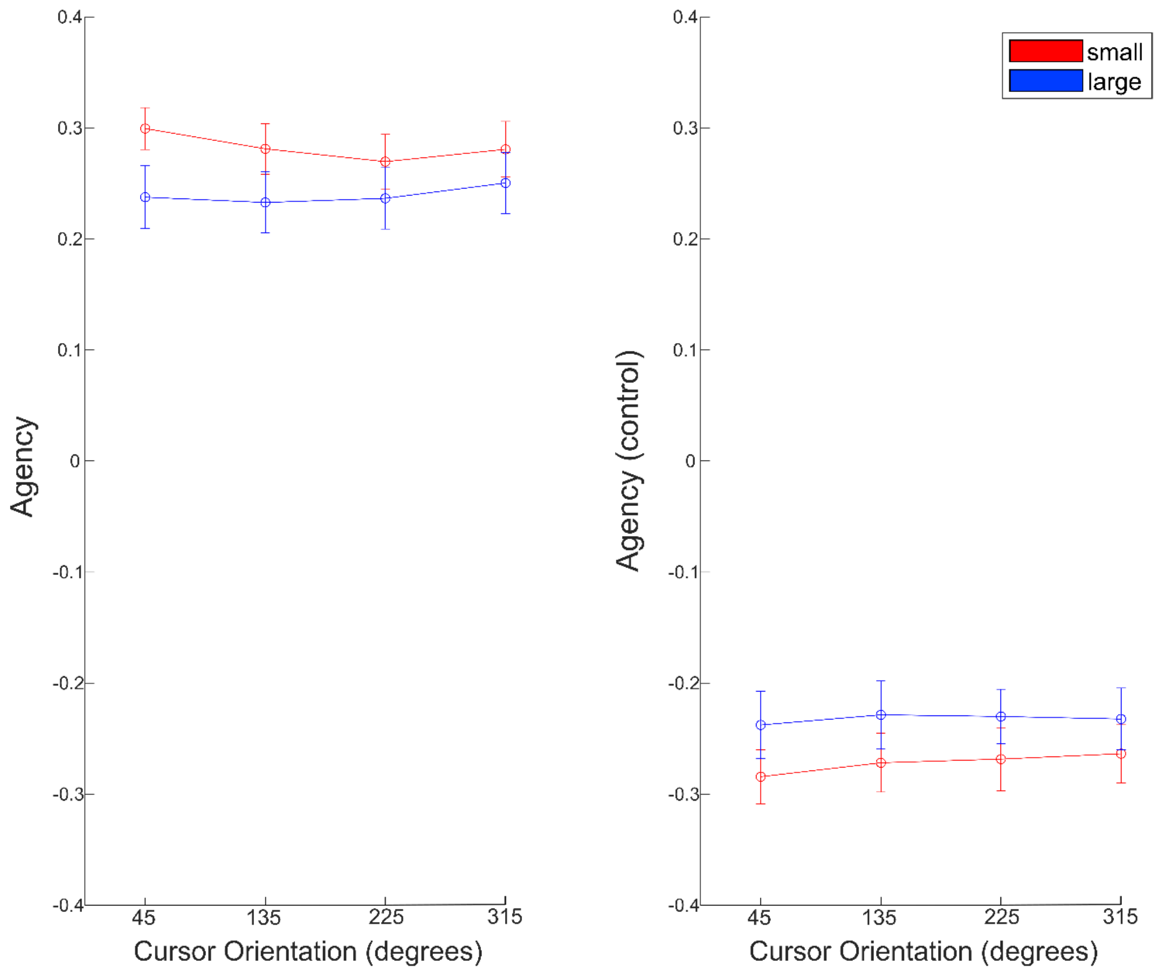

Figure 3.4.6 shows the rating for the agency statement and the agency control statement for the small and large cursors, averaged for each cursor orientation. The rating bar goes from -0.4 “Not at all” to 0.4 “Very much” as this was the screen position of the rating bar in a.u. Error bars show standard error.

After each set of trials, participants were asked to rate their subjective feelings of agency and familiarity over the cursor movements.

The first rating statement was “I felt I was controlling the cursor”. We expected the smaller cursor at 45° rotation to produce the highest ratings of agency over the movement. Also, since the larger cursor is less familiar and takes up more screen space, we would expect that the orientation would have less effect on feelings of agency and familiarity, as these would already be diminished.

A two-way repeated measures ANOVA (two cursor sizes, four cursor orientations) was performed in Matlab (Trujillo-Ortiz, 2021a) to compare the effects of these variables on the amount of agency the participants felt over the cursor movements. This revealed that there was a significant main effect of cursor size ($F(1,17) = 5.68$ $p = .029$). Participants felt more agency over the small cursor. There was no main effect of cursor orientation ($F(3,51) = 1.81$, $p = .158$) and no interaction.

3.4.5 Agency control

The second statement that participants were asked to rate was “The cursor seemed to have a will of its own”. Participants were expected to give the reverse ratings to the previous question and since the cursor was always under the control of the participant.

A two-way repeated measures ANOVA (two cursor sizes, four cursor orientations) was performed in Matlab (Trujillo-Ortiz, 2021a). This revealed that there was a significant main effect of cursor size ($F(1,17) = 5.54$ $p = .031$). Participants felt that the larger cursor was less under their control. There was no main effect of orientation ($F(3,51) = 0.84$, $p = .478$) or any interaction.

3.4.6 Familiarity

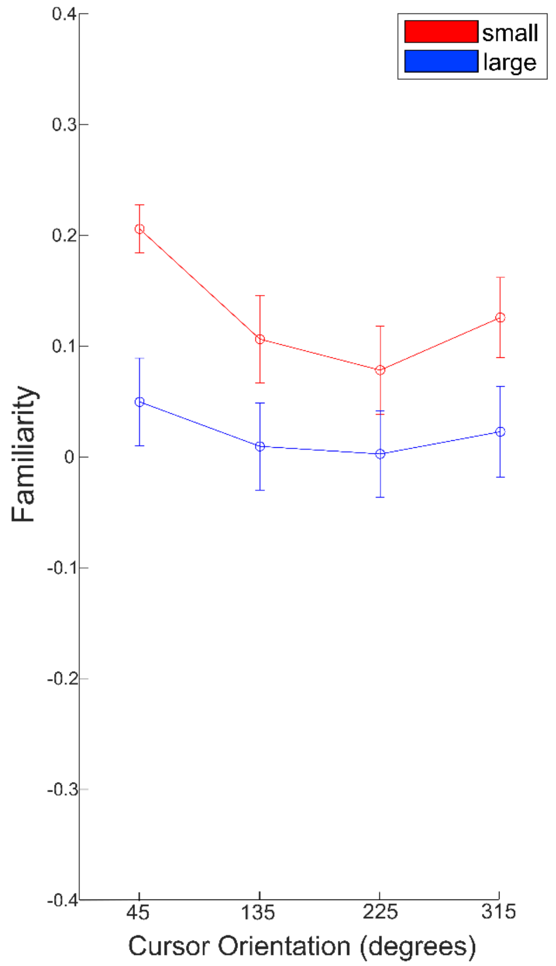

Figure 3.4.7 shows the rating for the familiarity statement for the small and large cursors, averaged for each cursor orientation. The rating bar goes from -0.4 “Not at all” to 0.4 “Very much” as this was the screen position of the rating bar in a.u. Error bars show standard error.

The third rating statement was “The cursor felt natural to me”.

A two-way repeated measures ANOVA (two cursor sizes, four orientations) was performed in Matlab (Trujillo-Ortiz, 2021a) to compare the effects of these variables on how natural the cursor felt to the participant. This revealed that there is a main effect of cursor size ($F(1,17) = 15.69$ $p = .001$), a main effect of cursor orientation ($F(3,51) = 6.16$ $p = .001$), and an interaction between cursor size and orientation

(F(3,51) = 3.53 p = .021). The large cursor felt less natural to the participants than the small cursor.

Perceived naturalness was highest for the small cursor pointing at 45°, significantly higher than 135° (t(17) = 2.86 p = .011), 225° (t(17) = 3.45 p = .003) and 315° (t(17) = 3.07; p = .007). Cursors at 225° were also significantly different from 135° (t(17) = -2.86, p = .011) and 315° (t(17) = -2.82, p = .012).

There were no differences in naturalness for different orientations when considering just the large cursor.

In summary, fastest completion times were found for cursors pointing to the familiar top-left. Larger cursors had longer completion times for targets that were backwards along the movement path. Cursor paths were more curved for the large cursor. Cursor paths were also more curved for targets that were orthogonal to cursor orientation in comparison to targets that were in line with the cursor orientation. This effect was more pronounced for the larger cursor. Participants felt more agency over the small cursor. Agency was more affected by changes in orientation for the small cursor than the large cursor. Participants also felt that the large cursor was less under their control. The small cursor at the familiar top-left felt the most natural to participants. The smaller cursor was again more affected by orientation than the large cursor.

3.5 Discussion

For many people in industrialised societies, being able to interact with computers efficiently to complete tasks and interact with the outside world is vitally important. In order to do this, they need to have effective UIs and also feel satisfied with the experience as many people spend most of their days online, depending on their work or if in they are in education and so on.

When considering optimal UIs, most studies have focused on target characteristics such as the size and spacing of icons (Jiang & Gu, 2020) rather than cursor characteristics such as size. UI developers adapt the screen to match the pointer without considering if it is the best possible configuration.

The current study aimed to investigate how familiarity with the size and orientation of the mouse cursor affected behaviour and the feeling of agency, without changing the responsive behaviour of the tool. To do this, participants completed a target-pointing task on a computer screen, with cursors that varied in size and orientation.

We expected to find that the smaller cursor at 45° rotation (pointing towards the top left of the screen) would have the best task performance as it is the most familiar to the participants, as well as higher feelings of agency and familiarity. We also expected that the larger cursor would have worse performance as it may obscure targets in certain locations on its approach.

The results support our previous findings on cursor characteristics and show that cursor size affects both pointing behaviour and the feeling of agency.

As predicted, trial completion times were significantly faster for cursors pointing to the familiar top left. According to Fitts (1954), movement of differing amplitude but equal difficulty will have the same duration, meaning that the trial completion time should not have changed unless the orientation change provided more information that needed to be processed. This suggests that the familiarity with the orientation of the cursor aided in task performance, allowing participants to more quickly plan and execute the motor movement, and was not affected by the size of the cursor. This could be because the tool matched the ingrained internal model that the participants had for the mouse cursor, specifically the expected position of the ‘hotspot’. Our results also support previous findings that bottom-right pointing cursors have the worst task performance (Po et al., 2005).

It was also found that the larger cursor had longer completion times for targets that were backwards along the movement path. This supports the idea that the larger cursor had increased potential for obscuring the target, making it harder to predict and execute the movement to accurately click the target. Participants may have anticipated this and approached the target more slowly, as there was no difference in deviation at the midway point for large and small cursors travelling backwards, discussed below. It is also possible that the adjustment was made towards the end of the movement. Finch and colleagues (2008) also found that the blunt end of the cursor moved faster, with these effects being during terminal guidance.

It has been found previously that non-congruent visual characteristics of a stimulus (in this case the spatial characteristics of the cursor) with the expected movement (the direction of the response) have a detrimental effect on performance (Fitts & Seeger, 1953), known as stimulus response compatibility, meaning that we would expect to have fastest completion times for movements to targets in the direction of the cursor (as found in Po et al., 2005). The current results do not support this, as no differences were found for completion times for orthogonal, forward or backwards movements when considering both the cursors. Training or practice with a certain tool could affect the immediate situation, i.e. the experiment, but would have little effect on the more general experiences and habits (Fitts & Seeger, 1953). However, Po, Fisher and Booth (2005) found that there were performance advantages for orientations that matched the direction of movement and argued that the stimulus response compatibility could never be fully trained away. In their study, all targets were visible on the screen, and participants had to click the highlighted target. It could be that participants were more able to plan their movements in this task, allowing them to benefit from congruent mappings of stimulus and response.

There was more of a deviation from a straight line for the large cursor, and for cursors pointing away from the participant (the familiar top left and top right). This was initially surprising as the curved line is less efficient but could mean that it is easier to plan the path for those cursors and curve around to approach the target from the tip of the cursor (as shown in figure 3.4.4). There was also once again less of a curve for cardinal target locations.

There were also interactions between cursor size, cursor orientation, and target location. The deviation from a straight line was more affected by cursor orientation for the large cursor.

Larger effects for oblique target locations can be attributed to the oblique effect. Yousif and McDougle (2023 p.2080) suggest that this effect is due to “deficits in angular acuity in the oblique regions of space” which result in poorer performance on pointing tasks and orientation judgments that are further from the cardinal axes. There may also be a physiological component, with different movement angles being more difficult to physically complete, but since this experiment was conducted remotely, we are unable to draw conclusions about the direction and amplitude of physical mouse movements. It is possible that tasks performed with the physical hand are constrained by the biological limitations of the hand and arm; movements that are achievable in the virtual environment may have felt less natural and consequently adjustments to these movements may have been made to reduce discomfort or to continue learned behaviour.

Another measure of deviation that we assessed was the deviation from a straight line considering the relative position of the targets to the cursor orientation. We found that there was a main effect of target location relative to the cursor orientation. Participants moved the cursor in more of a curve to reach targets that were orthogonal to the cursor direction, in comparison to targets that were in line with the cursor direction, so that the point would have to be moved either forwards or backwards to reach the target. An interpretation offered in the previous chapter is that it is easier to plan movements along the cursor's axis, rather than against it. There was also a main effect of cursor size, as this was more pronounced for the larger cursor.

Due to the shape of the cursor and relative position of the hotspot, non-congruent trials (where the hotspot is not pointing towards the target at the start of the trial) could mean that the target is obscured by part of the image, especially for the large cursor. This could have influenced the increase in path deviation as participants are curving the movement path so that the point of the cursor approached the target first. This could explain why participants curved more around the target with the large cursor. However, there was no difference in curvature for forward trials versus backwards trials, suggesting that planning the cursor movement along its axis is easier regardless of the point location. The cursors used were also transparent, with only the outline being opaque, which reduced the likelihood of the cursor fully obscuring the target.

We hypothesised that cursors pointing in the direction of target location would have faster trial completion times and a straighter path to the target, because the arrow could have a pre-cuing effect (as arrows can code direction, see Kantowitz, Triggs, & Barnes, 1990) and make planning the path to the target easier. This was not supported by the results, where there was no difference in trial completion times or deviation of the path for forward or backwards movements.

Other studies, such as Phillips, Meehan and Triggs (2003) found that arrow shaped cursors were slower and less efficient when pointing in the direction of the target. Although they only considered two orientations (top left and top right) and either compatible or incompatible movements, they suggested that this was because compatible distances were overestimated and that participants then had to spend more time making adjustments towards the end of the movement. This could be part of the Müller-Lyer effect (see Bruno, Bernardis & Gentilucci, 2008) where the same distance can be seen as longer or shorter whether it is bracketed by inwards or outwards facing arrows (<> or ><). Participants would judge the length of the necessary movement based on the central mass of the cursor (see e.g. Morgan & Glennerster, 1991) and so overestimated the distances as the cursor’s central mass is further away from the target than the cursor’s point in forward movement trials. This misjudgement would then require more adjustments to be made to get back on target than for continuing the path in undershooting conditions. Our results may have differed for the large cursor, which according to this illusion theory would underestimate the distance to the target, as the corrective movement would then be under a condition where the larger tail of the cursor is obscuring the target, thereby making it harder to accurately click. This could also explain why Po and colleagues (2005) found that forward movements were faster, as their targets were always visible and according to Bruno and colleagues (2008, p. 434) “the [Müller-Lyer] illusion has little effect when pointing is programmed from viewing the target rather than from memory”.

The results from the subjective rating scales showed that participants felt the most agency when using the smaller cursor.

The ratings for agency were always quite high, which was expected as participants always had the same level of control. There was no change to the input, meaning that the visual feedback of the cursor associated with the mouse movements was as expected, which has been reasoned to preserve the sense of agency (Gozli & Brown, 2011). There was also more of a deviation from a straight line for the large cursor, meaning that it could have felt less efficient to use, meaning that participants felt less in control.

While running a pilot of this experiment, one of the participants commented that the large cursor felt heavier, and that they expected it to behave differently since it was larger, like being harder to move, or have less velocity. If this was experienced by other participants, this could help explain the lower ratings for agency. This could be part of the size-weight illusion, where a smaller object is perceived to be heavier than a larger object of the same weight (Flanagan & Beltzner, 2000), because larger objects are expected to be heavier (Ross, 1969). Previous use of a real-world tool would have created an internal model whereby larger tools are heavier and harder to move. Since this was an online experiment, the only verbal reports were from colleagues that piloted the study, so further experiments in person would be needed to explore this phenomenon.

Further to asking participants if they felt they were controlling the cursor, they were also asked if the cursor seemed to have a will of its own. This was designed as a control question as the participants were always in control of the cursor movements, and in the previous chapter the results for the different cursor images and orientations were not significant from each other, as expected. However, in this experiment, there was a main effect of cursor size, with participants feeling that the large cursor had a will of its own. This could also be due to the internal model with larger tools generally being heavier in the real world, as the expectation that the larger cursor should act or feel different could also make participants feel less in control because they make adjustments that are unnecessary. Correcting for those adjustments could then feel as though they are fighting against movements made by the cursor of its own accord. The results for the large cursor were still below 0 (towards the “not at all” answer) so this may have been a nearly imperceptible feeling.

Since the sense of agency was assessed through explicit ratings, the results might have been influenced by participants' expectations of the task's purpose and their pre-existing beliefs about what they should feel in response to the experimental changes (Gawronski, LeBel, & Peters, 2007). We have linked these reports to objective measures of task performance, but we must exercise caution when drawing conclusions from explicit judgments.

For familiarity, and how natural the cursor felt, there was a main effect of cursor size, with the smaller cursor feeling more natural, and a main effect of orientation, with top left feeling the most natural followed by the top left. Both of these orientations are possible when you consider the cursor representing a finger pointing at the screen and the biological limitations of the real hand. There was also an interaction between the cursor size and orientation. Post hoc tests showed that for the level of familiarity for the small cursor is significantly affected by orientation, but this is not the case for the large cursor, although it followed the same trends, they were not significant and much closer to the middle of the rating scale (a neutral answer). These results support the findings in the previous chapter, with the small cursor pointing at the top left feeling more familiar than both a large cursor and a hand shaped cursor at other rotations. Together, we can infer that when the stimulus was already unfamiliar in one aspect, there was a floor effect where further unfamiliar changes were unable to significantly alter the perceived naturalness.

Other studies have made suggestions for updated cursor designs, such as orientation neutral cursors (such as a crosshair, see Phillips, Triggs & Meehan, 2001), fan cursors that change their activation area according to movement velocity (Su, Au, & Lau, 2014) or dynamic and tailored cursors, such as directional cursors that point to the direction of movement when menu options or other interactive elements are in one area of the screen (Po et al. 2005), to better support stimulus response compatibility. Different cursors will have different associated problems, for example the crosshair cursor is difficult to see at the extreme top and bottom of screen, and the arrow cursor is worse at bottom and right side of screen as most of the image is obscured (Yamanaka, 2018). Whole hotspot cursors have also been suggested, especially for people who struggle with fine motor movement (such as older adults in Worden et al., 1997). According to Fitts' law, button pressing tasks are easier when the tool is larger than the button, as it increases the effective size of the button (Hoffman & Sheikh, 1991). This usually does not apply to cursors, which tend to have a single hotspot, but for whole hotspot cursors becomes relevant. Worden and colleagues (1997) found no detrimental effect for targets close to each other when using whole cursor hotspot, as the target nearest the centre of the cursor was selected.

It is assumed that people intuitively know which part of an arrow cursor is the hotspot. In future experiments participants should also be asked if they still intuitively saw the point of the arrow as the hotspot when it was pointing towards them. It is possible in an experimental setup that it could be wrongly assumed that the hotspot had been moved (so a cursor pointing bottom right could have the hotspot at the usual location of top left, with the tail becoming the new hotspot). This is unlikely given that for the majority of trails participants clicked on the target, but would be a useful addition to rule out any effects of task performance, particularly for larger cursors which would have been further from the target if the tail was positioned at the centre of the target on click.

However, although good arguments are made for the various alternative cursors, our results suggest that the familiarity with the current arrow cursor is so entrenched that, even if there is demonstrable increase in performance, the feeling of being less in control could cause people to resist the change and not want to engage in the system that uses the updated cursor. Changes would cause reduced user satisfaction, so if a company deployed a new cursor UI to increase productivity by more efficient task completion, productivity could go down because the workforce is not happy with the change. They could also view having to overcome entrenched habits with current cursors (see Chong, Kee, & Chaturvedi, 2015) as too much mental workload, even if increased compatibility reduces workload in the longer term (Parasuraman & Riley, 1997).

Although the small cursor was closer in size to the standard cursor used for most modern displays, one design limitation is that both cursors would likely have been larger than participants would have been familiar with. Since the sizes were in arbitrary units, this would have also varied by screen size and resolution. Ideally the experiment would be completed in person so that we could ensure that they would be a standard size for everyone. The cursor was also symmetrical to allow for rotation (as in Po et al., 2005) but this could have also affected the familiarity ratings.

It was suggested that cursors are pointing to the top left as that would most naturally mimic a hand pointing at the screen, this assumes that people sit centrally to their screen with their mouse to one side. Inferences about the positioning of the participants’ hands are limited by the fact that this experiment was carried out remotely through an online platform. People sit at different positions in front of their PCs with varying mouse positions; for example, if the mouse is positioned more to the side, the hand position could have an angle more consistent with the 315° cursor (top right). Further experiments would hopefully take place in-person so that positioning could be the same across participants, perhaps inviting them to indicate their regular setup by dragging a keyboard and mouse on a schematic to assess familiarity with the experimental setup. This could also be done with an online experiment, so although the setup would not be standardised, we would have an indication of how participants are positioned during the task.

The pre-experiment questionnaire captured system information and information about how participants generally used a mouse, however there is no way to guarantee the accuracy of self-report. Again, an in-person setup would be optimal.

Our experiment also included participants that identified themselves as left-handed or ambidextrous, as long as they usually use the mouse in their right hand. This may affect their level of control, and congruency with the hand they may usually point with, but meant that they were still using the configuration that was most familiar to them. Young, Chen and Shentu (2016) found that for all participants, including those who were left-handed or ambidextrous, responses made with the right hand were faster than those made with the left. This supports the idea that familiarity is task-specific, and that practice with the mouse in the right hand overrides more general familiarity with using their dominant hand.

Other studies included an orientation neutral cursor such as a crosshair (Worden et al.,1997) or a circle, which was even found to have the best performance (Po et al., 2005). Future studies should also take these into account. Diagonal lines are easier to see against the predominantly straight lines (Treisman & Gormican, 1988) that are typical of UIs, so a crosshair cursor may be harder to see if it had vertical and horizontal lines. For the circle cursor, it would have been intuitive that the hotspot is central but could mean that targets smaller than the cursor are more likely to be obscured, especially if we are looking at cursor size. Since cursor paths in our experiment were likely curved to allow the cursor to approach from the point, having an orientation neutral cursor may allow a more direct path to be planned and executed.

Further studies that reduce the actual control that participants have over the cursor, such as adding jitter (Brenner & Smeets, 2023) or perturbing the movement, could reveal whether the different cursors are more affected by actual differences in control, rather than perceived differences.

This paradigm could also be extended into a more embodied setting, by changing the size of a hand in a pointing task in a virtual environment. The seen movements would be mapped more closely with the actual hand movements, potentially increasing the feeling of agency, while also allowing an induced sense of ownership over the hand. The next experiment will be using this to further explore the effects of the size of a virtual tool on task performance.

Chapter 4: The effect of virtual hand size on pointing behaviour and the sense of ownership and agency

4.0 Abstract

The feeling of ownership, such as the perception of ownership of an avatar in virtual reality (VR), can be induced through multisensory correspondences between the senses. These are generated when making active body movements and visually observing our own movements at the same time in the virtual world. These movements, when they correspond with the intention to move also give us a feeling of agency, or the authorship over our movements. The visual characteristics of a virtual limb can also be changed drastically from the real limb; a virtual arm can be longer or shorter and still be embodied. Previous studies using Fresnel lenses have found that minified hands exaggerate pointing movements. The current experiment aimed to look at how changing the perceived size of the hand affected pointing behaviour in VR, along with the senses of ownership and agency. Participants completed a pointing task where the size of a realistic virtual hand was varied. After each set of trials, participants rated their feelings of ownership and agency using a sliding scale, which was presented in the virtual environment. The results showed no difference in pointing behaviour or the sense of agency. The sense of ownership was highest for the size-matched virtual hand. This suggests that perceived distance caused by Fresnel lenses drove previous findings with pointing behaviour, but further studies are needed to compare these directly.

4.1 Introduction

In the previous chapter we looked at how changing the size of a tool can affect pointing behaviour and subjective feelings of agency in a target pointing task on a 2D screen. This paradigm could also be extended into a more embodied setting, by changing the size of a hand in a pointing task in a virtual environment.

Previous studies have found that people use the relative size of their hands to judge the size of objects around them (Linkenauger et al., 2013). For example, if an individual’s hand is magnified, it makes non-magnified objects presented near the hand appear smaller (Linkenauger, Witt & Proffitt, 2011).

In a target pointing study using a Fresnel lens to either magnify or minify the participants hand (van Dam & Ferri, 2017), it was found that participants exaggerated their movements (e.g. pointed further to the left for leftward targets) when using the minified hand. The opposite was found for the magnified hand, with decreased movement range. This suggests that people compensate based on the visual characteristics of their hand, making larger movements to make up for the perceived smaller size of the hand.

Hay, Pick and Ikeda (1965) suggest that we rely more on the visual information for positioning our hands, as opposed to proprioceptive information. They used a wedge prism to displace the seen location of the hand and found that the felt position of the hand was also displaced. However, the authors also mention that the shape and distance of the hand was also reported as strange.

Distorting sizes using a Fresnel lens or prism goggles also means that other properties of the environment are changed (Linkenauger et al. 2013), such as perceived distance. Other real-world manipulations, such as introducing a tool to change the body's capabilities could also make a task harder, for example, as it requires recalibrating the relationship between the sensory inputs (Takahashi & Watt, 2017). Another way to change how a person perceives their own body is through embodiment illusions.

Multisensory integration, that is the ability to combine information about an object or an event across multiple senses, allowing us to more reliably locate and react to a stimulus (Stein & Stanford, 2008). When these signals relate to what we can feel or see ourselves doing, it gives us a feeling of ownership over our body, we become aware that our body belongs to us (Ismail and Shimada, 2016). When we receive congruent signals, such as visuo-tactile information (Botvinick & Cohen, 1998) or proprioceptive information (Sanchez-Vives et al., 2010; Ismail and Shimada, 2016) that matches our seen movements, it can cause an illusory sense of ownership over the fake or virtual limb. For paradigms that involve voluntary movement from the participant, and movements of the avatar match the intended movements, the sense of agency arises, we have a sense of authorship over that action (Ismail and Shimada, 2016).

In virtual reality, the congruent movement seen from the first-person perspective coupled with unseen sensations of moving one's own body gives the illusion that the virtual body is our own (Sanchez-Vives et al., 2010). However, the virtual body may not match our own internal representation of our own body. It has been found that this illusory sense of ownership can also be introduced when the virtual body differs from the real body. For example, people can embody avatars of a different age (Banakou, Groten, & Slater, 2013), from a different race (see for example Peck et al., 2013) and even experience changes in implicit bias that last beyond the experimental setting (Banakou et al., 2016, see also Slater and Sanchez-Vives, 2014). During these illusions, participants treat the virtual body as if it is their own (Maselli & Slater, 2013).

The visual characteristics of a limb can also be changed drastically from the real limb, for example a virtual arm can be longer or shorter and still be embodied (Kilteni et al., 2012). Cowie and colleagues (2022) found that children and adolescents embodied to different sized hands using the RHI paradigm went on to judge their own hands as having changed size after the illusion.

Van der Hoort and colleagues (2011) argue that body size can affect how we perceive the world. In their experiment, participants felt illusory ownership over bodies that were either doll sized or giant, using a first-person perspective of the body and synchronous tactile stimulation. They found that participants judge distances to be further when embodied to the doll sized avatar: when instructed to walk towards a previously seen object with their eyes closed, they took more steps to where they thought it was located. The participants made spatial judgements relative to the size of their seen body.

Linkenauger and colleagues (2013) changed the size of participants' hands in VR and found that estimation of the size of a virtual sphere presented near to the virtual hand increased as a function of the size of the virtual hand. They did not find the same results when comparing this with scaling of familiar items, such as a pen, which was presented near the sphere instead of the hand, suggesting that it was not familiarity with an object and its usual size but that there was a special relationship with the size of one's own hands and how we see the objects in our environment. Proffitt and Linkenauger (2013, p.171) argue that "visual information is not combined with, but rather is scaled by, nonvisual metrics derived from the body" so for example in a target pointing task, the body is acting as a pointer, and the distances would be viewed relative to what the body can reach.

The ability to reach a target has been found to influence the perceived distance to the target in a virtual environment (Linkenauger et al., 2015a). Linkenauger and colleagues had participants estimate distances to targets with a visual matching task after reaching for the target with a virtual arm that was either longer or shorter than their real arm. The distance appeared shorter when participants were given a longer virtual arm, but only when they had experience of pointing with it. Very little experience was needed with the new length virtual arm before participants started using it to judge the relative distance to the target, suggesting that familiarity with one’s own arm length is not enough to persist in making judgements in the virtual environment, and suggests that the visual information being received is given more perceptual weight than the internal model of our own size and shape.

To be able to make judgements on what the body can reach, we need an internal representation of our body size and shape. Proprioceptive information, such as the sensation of stretching and contracting from the skin is not enough to tell us the length of limb segments and therefore their absolute location in space (Longo et al., 2010). By combining proprioceptive information with the internal body model, we can use that information to stay aware of the location of our limbs and make judgements on what actions are achievable, such as what actions can be taken by a certain body size, such as reaching distance and grasping ability (for example Linkenauger, Witt & Proffitt, 2011).

Embodiment illusions show that the internal representation of the body is not static and has an element of plasticity (Azañón et al., 2016). The internal representation has also been shown to modulate the illusion, however. For example, the Rubber

Hand Illusion can only be induced when the seen fake hand is in an anatomically congruent position (Tsakiris and Haggard, 2005), showing that the internal model can modulate embodiment illusions through top-down signals based on the visual representation of our own body (see also Pavani & Zampini, 2007). However, studies have found that the internal model is often distorted. In one study, participants were asked to compare the lengths of two body parts in a visual estimation task, revealing “dramatic systematic distortions in the perception of bodily proportions” (Linkenauger et al., 2015b p.103). Another estimation study found that participants exaggerated the width of their hands in comparison to the length when asked to point to locations of their hidden hand (Longo & Haggard, 2010). This demonstrates that we have a stable internal model of our hand size and shape but that it does not match the real hand.

It is unclear how the body model interacts with presented hands of different sizes when participants need to accurately use this information in a pointing task, as the relation between body representations and goal directed actions has received little attention (Azañón et al., 2016).

This study used Virtual Reality to manipulate hand size without changing other properties of the surrounding environment. We used a hand matched to the skin-tone of the participant, and either matched to the size of the participants hand, a small hand 50% of real size, or a large hand 200% of real size in a target pointing task. We were interested in how behaviour in a pointing task changed as a result of changing the perceived hand size before each movement.

Being able to accurately move and judge location is increasingly important as VR is used in a number of training applications (for a review see Xie et al., 2021) with this increasing use it is also important to see how various avatars change behaviour and the feeling of embodiment, in this case ownership and agency.

In our target pointing task, we expected pointing behaviour to differ, with participants having a more exaggerated pointing error with the smaller hand as found in van Dam & Ferri (2017). These Fresnel lens findings suggest that participants may exaggerate their movements with the small hand, in which case we would expect a leftward bias for leftward targets and a rightward bias for rightward targets. When using the large hand we could expect undershooting.

Van der Hoort and colleagues (2011) found that participants walked further to the distance they thought an object was located (with their eyes closed so the actual object location was hidden) when embodied to a doll-sized body. If the smaller or larger hand made participants feel they were a different size within the environment, as vision has traditionally been seen as the dominant sense in spatial perception (Power & Graham, 1976), target distance misjudgements could cause a bias to one side as the hand crosses the target wall on the z axis (depth) while still being on a trajectory to the target location on the x and y axes.

This could also be caused by a bigger hand implying a longer arm, and therefore the target would take up a smaller proportion of the arm's reach and appear closer (Proffitt & Linkenauger, 2013). Having a longer arm also increases the 'action boundary' which means we perceive the environment in terms of what the body can achieve (Proffitt & Linkenauger, 2013). Objects appear further for those with shorter arms (Linkenauger et al., 2015a).

Many studies have also concluded that space is perceived differently if it is within arm's reach or outside it (e.g. Longo & Lourenco, 2007; Linkenauger et al., 2015a).

Proffitt and Linkenauger (2013) suggest that apparent distances in near space are related to the length of reach or the size of the hand.

Since action boundaries are relative (Proffitt & Linkenauger, 2013), some actions are possible for someone with one hand size or arm length, but not another. Participants could feel less able to complete the task with a smaller hand as the implied arm length would be shorter. Having a target appearing further away if using the hand as a familiar object to scale the environment (Linkenauger et al., 2013) could also make the task feel more difficult, in which case we would expect participants to feel less agency over the smaller hand.

We expect participants to feel most embodied to the size-matched hand, as it is the most familiar to them and should most closely match the internal body model. Pavani and Zampini (2007) found that larger hands were more readily incorporated into the body schema than hands that were smaller than the real hand in an RHI paradigm. Therefore, we would expect ownership ratings to be lower for the smaller hand in this experiment.

4.2 Method

4.2.1 Participants

The study was approved by the Ethics Committee of the Department of Psychology at the University of Essex prior to data collection (ethics code: ETH2223-0153). The participants were naive with respect to the purpose of the experiment and informed consent was obtained from each participant prior to the experiment. The experiment was completed by 20 participants, aged between 18 and 37. Power considerations are included in Appendix A. All participants were right-handed.

4.2.2 Apparatus

Participants used an Oculus Rift Head Mounted Display (HMD), along with the Oculus Touch controller corresponding to their dominant hand to interact with the virtual environment.

We created the virtual environment using the “CustomHands Sample Scene” which was part of the Unity Sample Framework code (Meta, 2024) which provides the user with a pair of custom hands that can be moved around and posed, this was then modified for the purpose of the experiment. The virtual room that participants were placed in was 11.5 by 11.5 units wide, and 2 units in height (1 unit roughly corresponds to 1 metre in physical space) and the room consisted of 4 walls and a floor, with an open ceiling. The walls had the default grey texture, and the default skybox was visible through the open ceiling, which was a pale blue that fades towards the horizon, see figure 4.2.1 below. There was a transparent target wall 5 units wide, 2 units high, and 0.2 units deep, ratings questions were also presented on the surface of this wall. The position of the wall was such that its centre matched the body midline of the participant (based on the spawn location of the participant in the virtual environment), was 1 unit above the floor in the virtual environment and 0.595 unitts away from the centre of the spawn position of the participant. Unity (version 2017.1.0f3) was used to render the 3D content of the virtual environment.

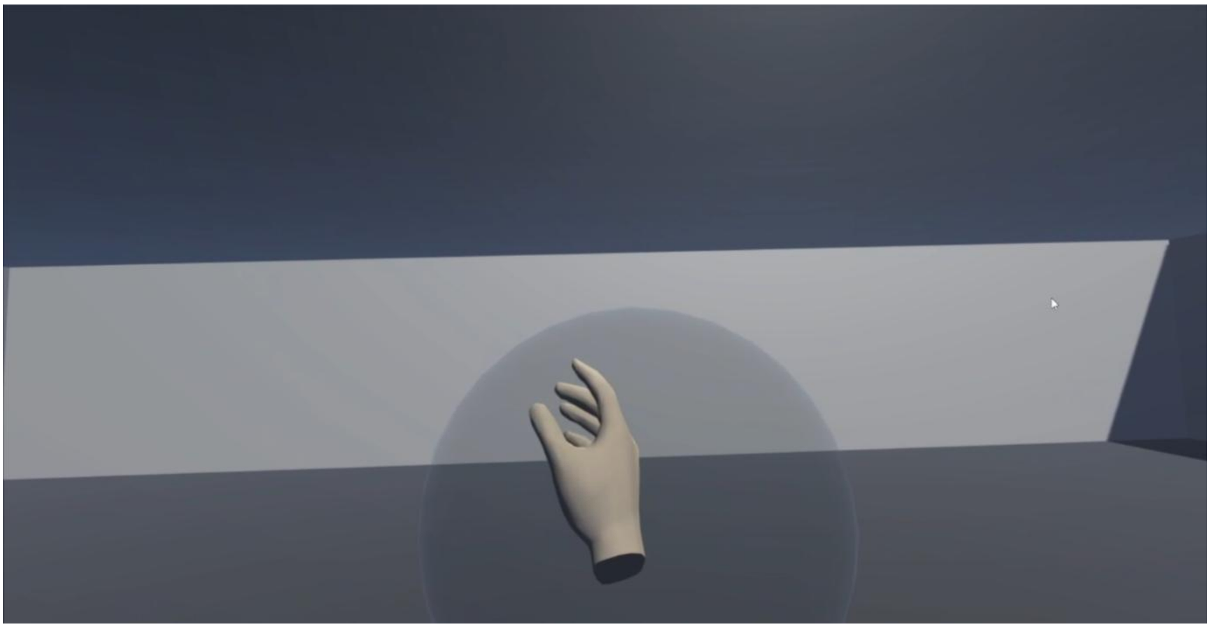

Figure 4.2.1 shows the size-matched hand in the starting orb.

Participants were seated in an office type chair with space in front to be able to move their arms freely and positioned so they were able to reach the targets on the central plane.

4.2.3 Procedure

Demographics and informed consent were collected prior to the experiment. Participants were asked to choose which skin tone they felt best matched their own from a list (as shown in Figure 7 of Akash, Mollah, & Akhand, 2016). Their hand size was then measured from the wrist to the tip of the middle finger and recorded in cm.

Participants were then seated on an office type chair that was central to the space to allow participants to both hold their hand comfortably in the starting sphere (described below) and be able to reach the targets on the central pane without having to move their body. The experimental procedure was then explained to them, and they were shown the controller and which buttons to press at different parts of the experiment and were able to adjust the VR headset so that it was comfortable.

The participant ID, handedness, chosen skin tone and actual hand size was inputted to the experiment dialogue box and the practice trials were started.

Participants were in the described virtual room and saw a transparent orb (diameter of 0.3 units which roughly translates to 30cm) 0.25 units in front of them, central to the space and 0.345 units away from the target wall. A representation of their hand in their chosen skin colour and matched to the size of their actual hand was visible when the hand was inside this sphere. This was displayed at the location that corresponded to the location of the real dominant hand from the participant’s viewpoint as they moved their hand. The hand was animated such that changing the positioning of fingers on the controller buttons was also represented in the virtual environment. An instruction was shown on the target plane: “Please keep hand within sphere".

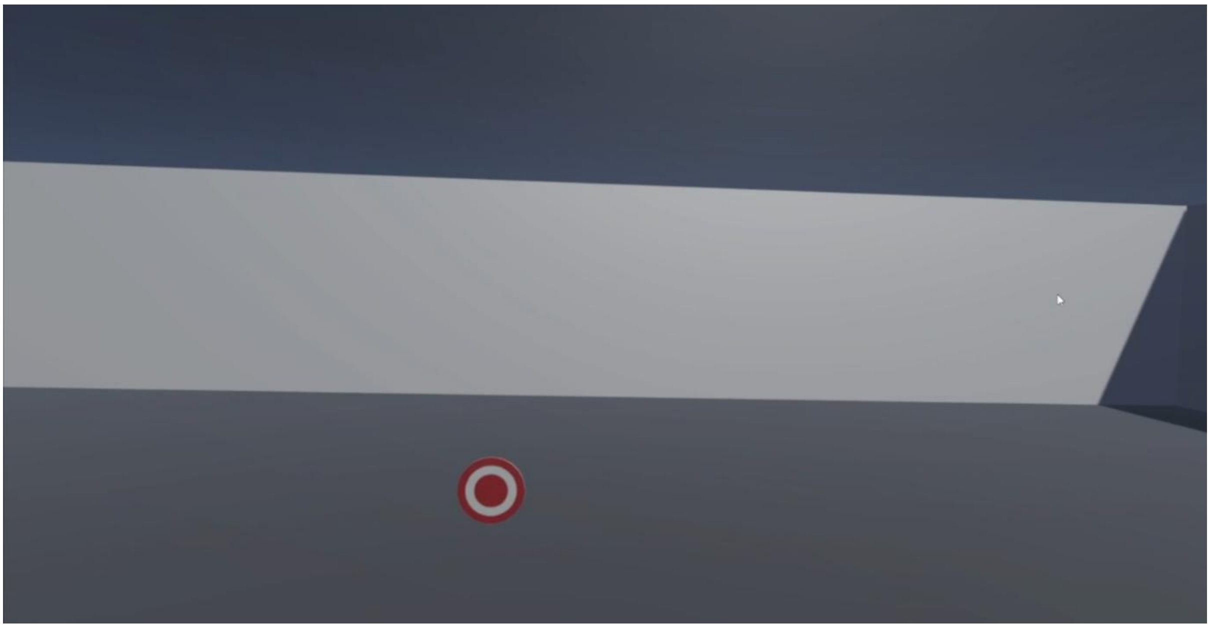

Figure 4.2.2 shows the presented target in the reaching phase where the virtual hand is hidden.

After 2 seconds of the hand being in the starting sphere, both sphere and hand were hidden, and a red-and-white ringed target with a diameter of 5cm (0.05 units) and 1mm thick appeared in a random position on the central plane. The range of space that the targets could appear on the target wall were between -0.25 to 0.25 units horizontally, and 0.9 to 1.1 units vertically. Instruction text was shown to tell the participants to “Hit the target". This is the movement phase where the participant was expected to move towards the target. Once a hit is detected (the virtual hand touches any point on the target wall), the trial end time was recorded along with the final hand position and the target was hidden. The recording continued for an additional 0.5 seconds to ensure the movement was complete. The full trajectory of the hand and orientation of the headset was also recorded on every frame. This was repeated for 10 trials. After each set of 10 trials, participants answered on-screen questions using a continuous sliding scale as used in van Dam and Stephens (2018).

The continuous scale ranged from “Not at all” on the left side (roughly 0.5 units to the left of centre on the virtual scale) to “Completely” on the right side (roughly 0.5 units to the right of centre on the scale). A setting of “not at all” on the one side related to a value of -0.25. A setting of “very much” related to a value of +0.25. The ownership questions were “I felt like the virtual hand was a part of me” and “I did not know where my actual hand was” (control). The agency questions were “I felt like I was controlling the virtual hand" and "The virtual hand seemed to have a will of its own" (control).

Figure 4.2.3 shows the rating scale as it was presented in the virtual environment.

Participants moved a marker on the scale with the thumbstick of the controller to indicate their rating for the trial and pressed the trigger to confirm. This moveable marker always started at the central point. Once all ratings had been completed the next set of trials started, with the virtual hand being presented at the same size of the actual hand for the 5 blocks that made up the practice session. This allowed participants to become accustomed to the size and colour of the virtual hand that best represented their real hand.

Once the participant indicated that they were happy to continue and understood the task, the main experiment was started. This was the same procedure as the practice session, except that there were no longer written instructions to stay in the target orb and to hit the target. For each block a different hand size was presented to the participant in a randomised order: same size as the participants' actual hand, 50% of actual size and 200% of actual size. Each block consisted of 10 target hitting trials with a hand that stayed a constant size, followed by the 4 rating questions. The experiment consisted of 15 blocks, so each hand size was presented 5 times in a randomised order for a total of 150 trials for each participant.

4.2.4 Analysis

The error between target location and where the participant hit along the target plane in both the x and y directions was calculated. The data was then grouped by hand scale condition. We then used multivariate linear regression (mvregress, the Mathworks Inc, 2020) to analyse the relationship between the target positions and errors. Regression was used as the target positions were random so could not be directly compared between participants. The slope of the regression is indicating the systematic biases depending on location and these can then be compared between participants. This also aligns with the method used in the Fresnel lens study by van Dam and Ferri (2017).

We plotted the 'Error Slope X' and the 'Error Slope Y', and performed a Friedman test for each to see if there was a difference between the hand size conditions. We also plotted graphs for the average ratings of ownership, ownership control, agency and agency control for each condition.

The analysis was not pre-registered.

4.3 Results

4.3.1 Behavioural results

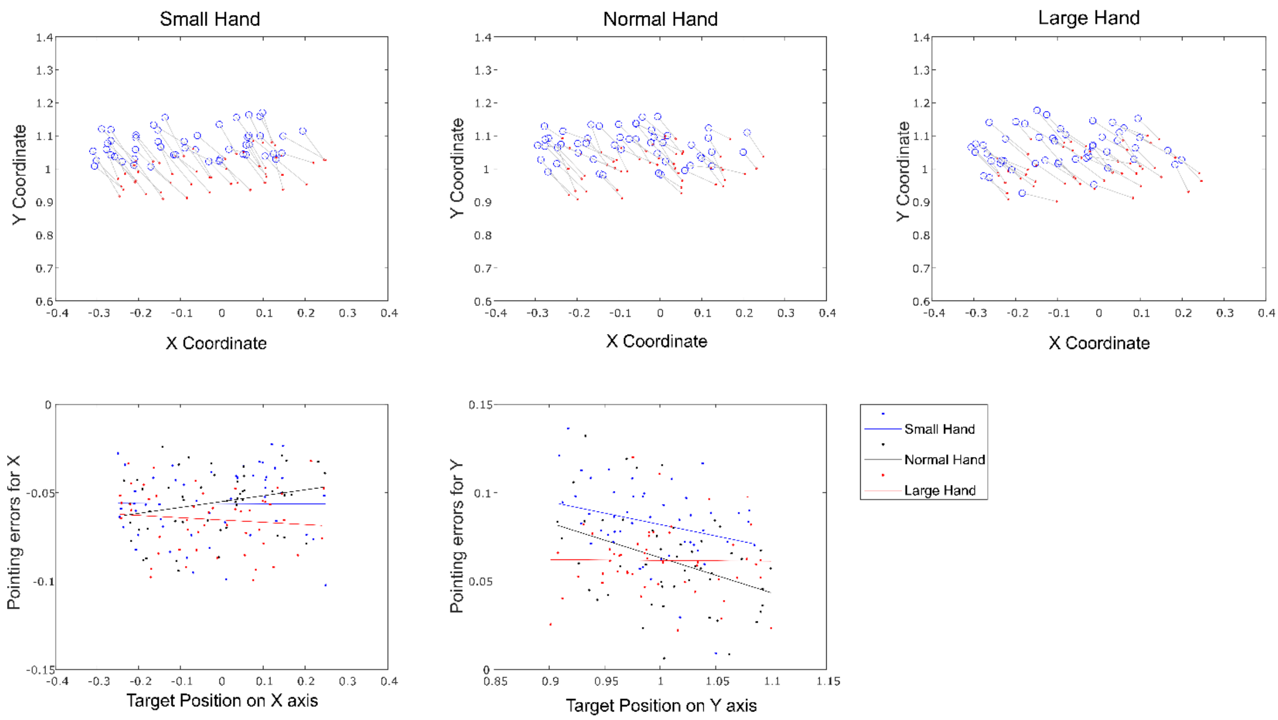

Figure 4.3.1 shows the results of an example participant. The top graphs show the position of the target as a red dot, and where the participant pointed as a blue circle. The lower graphs show scatter plots of target positions against pointing errors and fits a regression line for each hand size (mvregress in Matlab). Note that scales do not start at 0.

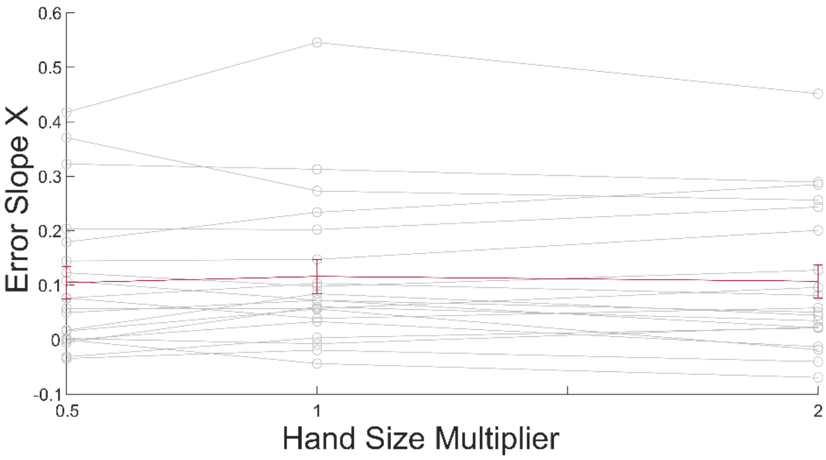

Figure 4.3.2 shows the value of the error slope for the X axis for each hand size. The slopes were obtained from the regression lines calculated for each participant as depicted above.

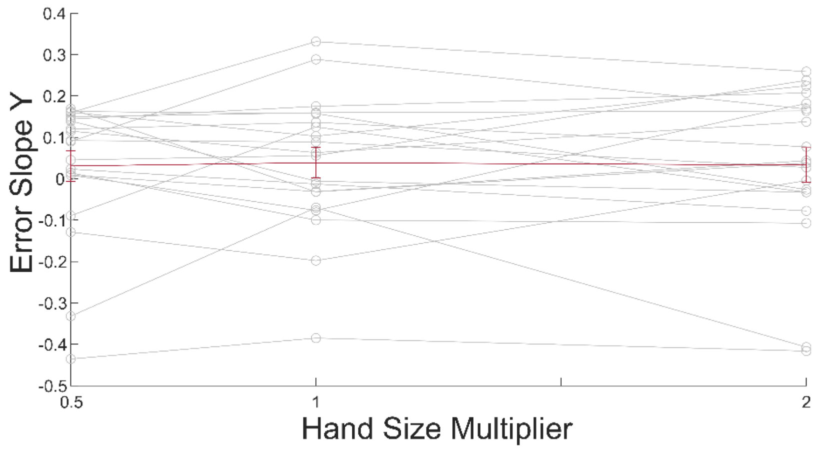

Figure 4.3.3 shows the value of the error slope for the Y axis for each hand size. The slopes were obtained from the regression lines calculated for each participant as depicted above.

We expected participants to have a more exaggerated pointing error with the smaller hand. No significant differences were found in the target pointing errors between any of the hand size conditions. Friedman tests were carried out on the pointing error slopes for both the x (Friedman χ^2 = 0.90 p = .638) and y (Friedman χ^2 = 0.10 p = .951) axes.

A positive slope would show an outwards/exaggerated bias. The graphs show that we have a very slight but not significant slope error for the x axis. A negative error slope would show inwards bias, with participants pointing more to the middle.

<u>4.3.2 Rating results</u>

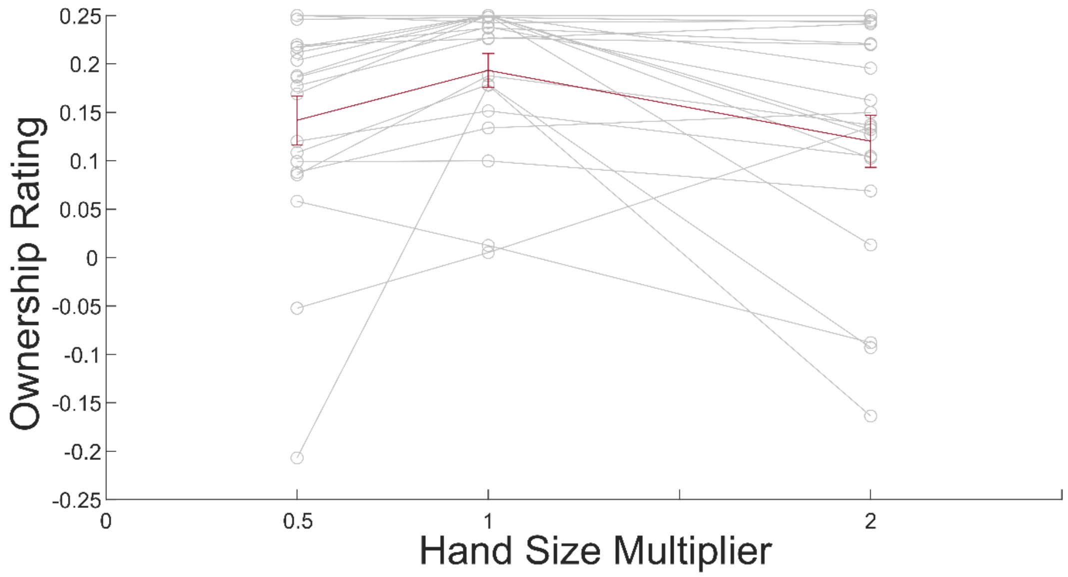

Figure 4.3.4 shows the ownership ratings averaged across participants for each hand size.

We expected participants to feel most embodied to the size-matched hand and ownership ratings to be lower for the smaller hand. In order to see if the participants felt more that "the virtual hand was a part of me" for different hand sizes, a Friedmans test was used. This revealed that participants felt that the hand size that most closely resembled their real hand size most felt like it was part of their body (Friedman $\chi^2 = 13.58$, $p = .001$). For all hand sizes, participants on average rated the feeling of ownership of the hand above 0, with the highest amount of ownership over the size-matched hand. Post hoc Wilcoxon signed-rank tests were performed in Matlab to see what hand sizes had different ownership ratings from each other. These revealed that the size-matched hand was significantly different from both the small hand (Bonferroni corrected $p = .003$) and the large hand (Bonferroni corrected $p = .015$). There was no difference between the small and large hands (Bonferroni corrected $p = .832$).

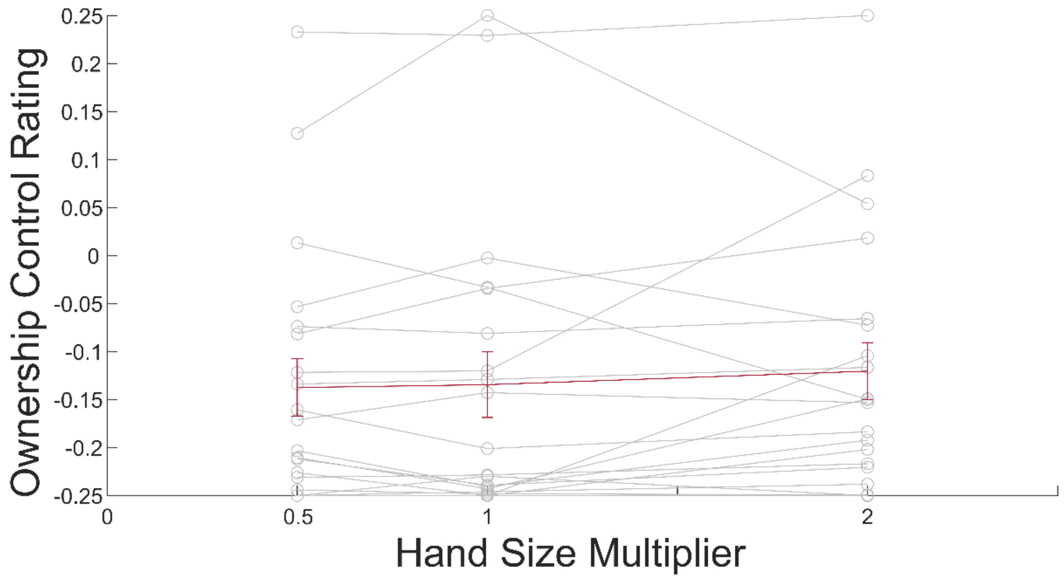

Figure 4.3.5 shows the ownership control statement ratings averaged across participants for each hand size.

As a control, participants were asked to rate the statement “I did not know where my actual hand was”. A Friedmans test revealed no significant differences between hand sizes for the control statement (Friedman $\chi^2 = 3.43$, $p = .180$).

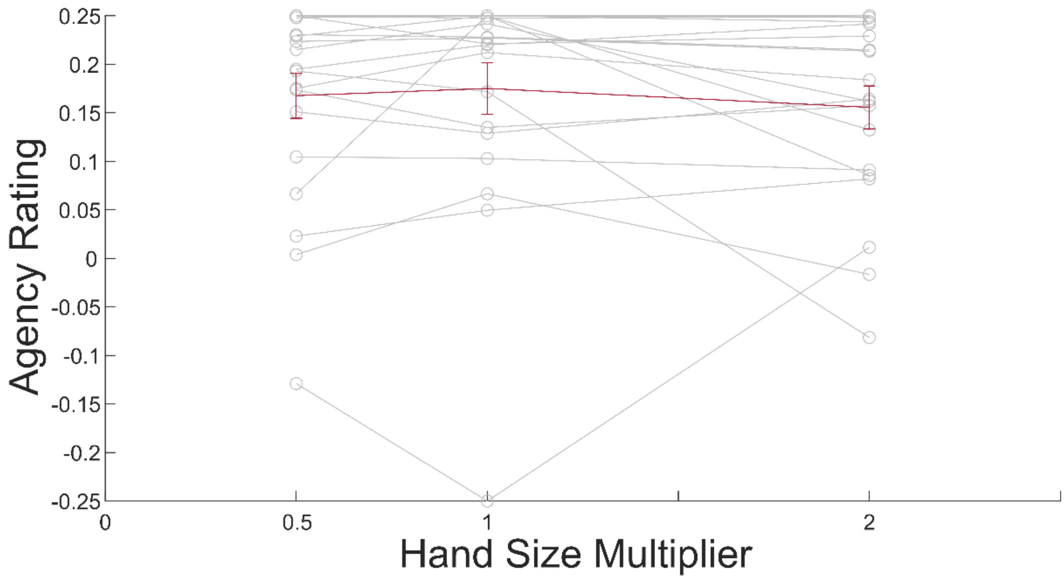

Figure 4.3.6 shows the agency ratings averaged across participants for each hand size.

In order to see if participants felt that they were “controlling the virtual hand", a Friedmans test showed no significant differences between hand sizes (Friedman χ^2 = 1.74, p = .418). Agency was always rated quite high on average.

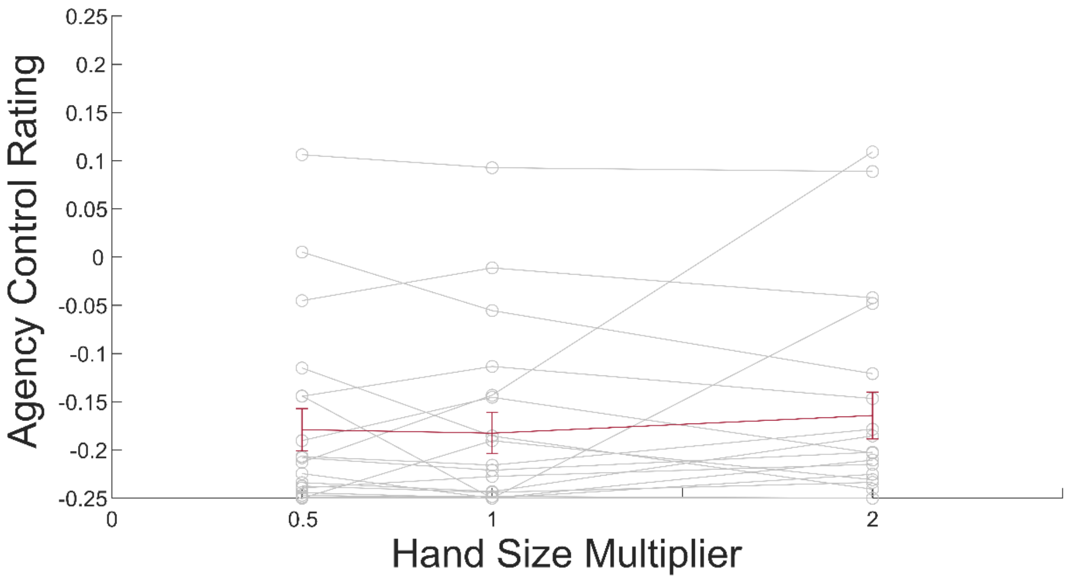

Figure 4.3.7 shows the agency control statement ratings averaged across participants for each hand size.

A Friedmans test also revealed no significant differences between hand sizes for the statement "The virtual hand seemed to have a will of its own" (Friedman χ^2 = 0.54, p = .765).

4.4 Discussion

In this study we were interested in how behaviour in a pointing task changed as a result of changing the perceived hand size before each movement. We also wanted to see if this change affected the senses of ownership and agency. To do this we used a target pointing paradigm in VR so that we were able to manipulate hand size without changing other properties of the surrounding environment.

In this task we expected pointing behaviour to differ, with participants having a more exaggerated pointing error with the smaller hand. Our results showed no movement bias with different sized hands. Each participant was biased in a different direction with their pointing movement and there was no difference between hand sizes. When looking at the error slopes, we had a very slight but non-significant positive slope, indicating an outwards bias, with participants exaggerating their hand movements in both directions. Size and distance are perceived differently in VR, but this tends to be a compression of perceived distance, found to be an average of 74% of modelled distance (Renner, Velichkovsky, & Helmert, 2013). It is also not biologically efficient to exaggerate movement, so it is unclear why this may be.

Previous VR findings have also shown that putting a participant in a different sized virtual body causes them to misperceive distances and size (see for example van der Hoort et al., 2011; Slater & Sanchez-Vives, 2014), hence we expected behaviour to change.

In our experiment, changing the size of the virtual hand may not have changed the feeling that the whole body was a different size, as eye height remained the same for all conditions. During a reaching task, the length of the arm is relevant to determining if a target is within reach (Proffitt & Linkenauger, 2013). Linkenauger and colleagues

(2015b) found systematic distortions in people's perceptions of the proportions of their own body relative to other body parts, with arm length being overestimated in comparison to hand size. Therefore, changing the size of the hand would not have changed the perceived reachability of the target, meaning that behaviour could stay the same for each condition without any compensations for perceived target distance.

The Fresnel lens findings (van Dam & Ferri, 2017) showed a difference in pointing behaviour between the different hand sizes, with participants exaggerating their movements with the small hand in order to make up for the smaller perceived size in an open-loop pointing task. Our findings suggest that it was the perceived change in distance caused by the way the Fresnel lenses work (i.e. magnifying or minifying the environment along with the hand, making targets seem closer or further away) that drove the changes in pointing behaviour. A further experiment in virtual reality would also manipulate the perceived distance to the target to compare to a change in hand size to determine what is causing the change in pointing behaviour.

When considering the ratings for ownership, we expected participants to feel most embodied to the size-matched hand, as it is the most familiar to them and should most closely match the internal body model. This was confirmed by our results, with participants rating the statement that "the virtual hand was a part of me" higher than for the other hand sizes. There were no significant differences between hand sizes for the statement "I did not know where my actual hand was", which was expected as the virtual hand was always presented at the same location as the real hand.

Pavani and Zampini (2007) found that larger hands were more readily incorporated into the body schema than hands that were smaller than the real hand in an RHI paradigm. Therefore, we expected ownership ratings to be lower for the smaller hand in this experiment, which was not the case; there were no significant differences in the feeling of ownership for the small and large hand. However, this could have been affected by the way the larger hand was presented. When any of the hand models were on the edge of the starting sphere boundaries, they would flash (which was unintended). This happened more often for the larger hand due to the increase space it took up, so this could have reduced the feeling of ownership for that hand.

We also expected an effect of hand size on the sense of agency, as having an unfamiliar size may have made the task seem harder. This was not supported by the ratings data, with no significant differences in the sense of agency for different hand sizes. This rating was always quite high, as participants always had the same level of control over the virtual hand. We previously found that the size of a cursor affected the sense of agency. This could be demonstrating a difference between using something that is seen as a tool, such as the cursor, which was affected by familiarity, versus using a representation that feels as though it is part of the body.

Unlike in the cursor experiments, there was also no feedback as to how well participants were performing, as the virtual hand was hidden during the movement phase. The trial ended whether it was the target or target wall that had been hit, so participants would be unable to use visual cues to update their internal motor model. This is important as the sense of agency depends on our ability to see the effects of our movements visually. However, in this case participants would have seen that their performance was not different across sizes, and so this may still have not altered the sense of agency for the different sized hands.

The virtual hand animations that reflected the hand positioning on the controller would have helped increase the sense of ownership and agency. However, these movements may have been more relevant to a grasping task (Proffitt & Linkenauger, 2013) and not to a reaching task. There were no practice reaching movements with the hand visible. Linkenauger and colleagues (2015a) found that there were no differences in estimated distances with long or short arms if participants had no experience of reaching with it, even though they could move the arm and place it on the table. In order to have behavioural differences, a practice trial with visible feedback of the reaching hand may have been necessary as that may update the relevant internal motor model.

There were a few limitations with the experimental setup that will need to be addressed for future experiments. Firstly, participants found it harder to reach targets when they had to reach across their body, so targets that were further leftward for righthanded participants may have been affected by positioning (for example see Bryden & Roy, 2006). This was especially true for participants with shorter arms who also struggled to find a comfortable position where they could both easily hold their hand in the starting orb and reach the targets. More piloting around target distance and positioning with people of different sizes would be beneficial.

Some participants found it hard to find the skin tone for the virtual hand that best matched their own, and some commented that the colour across the hand was uniform, which is not natural especially for participants with darker skin. Haans and colleagues (2008) previously found that realistic skin texture increased the strength of the RHI for hand shaped objects. In future a wider range of tones that are applied more naturally to the representation would be better for the feeling of embodiment.

As mentioned previously, the representation of the hand flashed on and off when intersecting with the bounds of the starting sphere, which we were unable to correct before the experiment was undertaken, which may have affected the extent of the embodiment of the larger hand in particular.

It has been found previously that size affects judgement on distance. Our virtual setup was very sparse, and participants may have used the size of their virtual hand to calibrate the distance in the virtual environment in the absence of other depth cues. In their experiment, Linkenauger and colleagues (2013) used many depth and size cues in their environment by placing many familiar objects in the scene but did not scale the virtual hand to match the participant. We had a training session with the size matched hand to try to ensure that it was that hand that was used to judge the distance, but a useful measure may have been to get the participants to perform a distance estimation task with the different sized hands to see whether any distance recalibration occurred with different hand sizes.

One study found that having a visual representation of the body only improved distance judgements if they felt ownership over that avatar, and that it was located in the same space as their real body (Leyrer et al., 2011). Changing avatar size to see if it also changes perceived difference also changed the feeling of ownership in our current study, which means that future studies looking at perceived distance change with a change in hand size would need to control for ownership.

It is possible that the difference in the feeling of ownership for the size-matched hand was due to response bias or demand characteristics. We would have liked to link task performance with the subjective ratings, however there was no difference in pointing behaviour. It may have been obvious to participants that the size-matched hand was the default as it was also used for the training portion, as we wanted the participants to feel embodied to that hand, but that may have unintentionally suggested what results we were expecting.

Being able to accurately move and judge location and distance is increasingly important as VR is increasingly used in training paradigms (Xie et al., 2021). The extent to which avatars that are visually different from the user can be embodied needs to be understood if they are to be used in medical settings, such as a surgeon controlling a minified robotic version of themselves to undertake delicate surgeries (van der Hoort et al., 2011). Our results suggest there are no behavioural biases caused by the change in size, however they did show systematic under or overestimation of distances that varied by participant, so this will have to be considered carefully.

Chapter 5: The effect of delays in a virtual tracking task on the feelings of ownership and agency

5.0 Abstract

The feeling of ownership, such as the perception of ownership of an avatar in virtual reality (VR), can be induced through multisensory correspondences between the senses. These are generated when making active body movements and visually observing our own movements at the same time in the virtual world. Feedback delays, which destroy this correspondence, are detrimental to the feelings of avatar ownership and agency in VR. Here we investigated the mapping between the delay, behavioural task performance and the ratings for ownership and agency. In particular we were interested in the degree to which reductions in ratings of ownership and agency with increasing delay are related to the increased spatial tracking errors and tracking lags that this introduced.

Participants performed a target-tracking task with various delays. The target object was a sphere that moved in three dimensions and participants controlled a second virtual ball to track the target. Delays of 0, 150, 300, 450, 600 or 900 milliseconds between the participants' hand movements and the virtual movements were introduced. No-delay trials were interleaved to avoid potential adaptation effects from influencing the results. After each trial, participants rated their feelings of ownership and agency using a sliding scale, which was presented in the virtual environment.

The results show that with increasing delay both spatial tracking error and tracking lag increased as expected (i.e., task performance decreased). In a similar fashion, the ratings for ownership and agency decreased with increased delay, and were both negatively correlated with the spatial tracking error and tracking lag. These results

indicate that task performance and subjective ratings are similarly affected by the delay. This raises the question of whether the subjective ratings might be linked to perceived task performance which will be the focus of future work.

5.1 Introduction

Virtual reality (VR) is a great tool that is being more widely used in education and training. It has been used in construction and engineering, such as health and safety training and training with specific equipment and tasks (Wang et al., 2018) and also for training in emergency situations (see Xie et al., 2021 for a review). Wang and colleagues (2018) note that there are many advantages to using VR in an education setting as it allows students to interact with each other in a virtual environment, which is especially important given the increase in distance education in recent years. It also allows training in fields where it would be expensive or even dangerous to attempt the action in a real-world setting (Xie et al., 2021). Interactions with objects in the virtual environment can be visualised in real-time (Park et al., 2016) thus allowing students to get a better understanding of a task through practice in a controlled and safe environment.

In order for VR to be effectively used for these applications, users need to feel present in the environment (Grassini et al., 2020). This usually involves giving the user a representation of their body that they can use to interact with the environment, known as an avatar. The perception of ownership of an avatar in VR, that is, feeling as though the virtual body belongs to us (Blanke, 2012) can be induced through multisensory correspondences between the senses (Shibuya, Unenaka, & Ohki, 2018). These are generated when making active body movements and visually observing our own movements at the same time in the virtual world.

This requires the different modes of sensory information to be combined in the brain in an optimal fashion. The temporal binding window, that is the period of time over which multiple stimuli can be combined to produce a single percept (Venskus et al., 2021) varies by individual with an average of around 211ms (Constantini et al., 2016). We often integrate self-generated sensory information (such as our felt position in space) with externally generated information (such as tactile or visual information on what we are interacting with, see Grechuta et al., 2019). We need to make decisions about how these sensations should be interpreted, whether they are relevant to the body and therefore interpret what is part of the body and what is not (body ownership). Determining the relevance of the signal with respect to the body is important for goal-oriented behaviour (ten Oever et al., 2016).

Therefore, if there is a delay between the modes of sensory information, such as when someone experiences lag in VR so that their seen movements are behind the felt location of their limbs, this would be detrimental to the feeling of ownership over the virtual avatar and also on task performance.

Temporally discrepant tactile and visual information has been found to reduce the illusory sense of ownership over a fake hand in the Rubber Hand Illusion (RHI), which is one of the first experiments looking into multisensory correspondence and the illusory sense of ownership, carried out by Botvinick and Cohen (1998). This illusion used synchronous or asynchronous tactile sensation on the participants' real hand, which was obscured from view, paired with the visual brushing of a seen fake hand. The combined visual and tactile information gave participants the sense that the fake hand belonged to them. When these stimuli were asynchronous, feelings of ownership over the seen fake hand were diminished. Other studies have found that the sense of ownership was diminished when the delay between seen and felt sensations were over 300ms (which is thought to be outside of the temporal binding window for visuo-tactile stimulation, see for example Bekrater-Bodmann et al., 2014; Shimada et al., 2014). This suggests that the temporal constraints of the illusion are part of the same mechanism for multisensory integration (Constantini et al., 2016).

Congruent visuo-tactile stimulation alone has been found to be strong enough to induce the sense of ownership over a non-humanoid object such as a table (Armel & Ramachandran, 2003). Bottom-up processing has therefore been proposed as a mechanism for the illusion, that is, the view that the synchrony of the stimulation was enough on its own to elicit the feeling of ownership over the fake limb (Botvinick & Cohen, 1998; see also Kilteni et al., 2015).

Illusory ownership over non-humanoid objects, however, has not been replicated with the passive RHI paradigm and is widely contested (see e.g. Tsakiris & Haggard, 2005, Haans et al., 2008). Findings have supported that the illusion is also modulated by the top-down internal model of our body's dimensions (Grechuta et al., 2019). The passive RHI needs the fake hand to be similar enough to the real hand in terms of its physical characteristics (both shape and posture, see Tsakiris et al., 2010) and anatomical plausibility (i.e. at an angle that would be achievable by the real limb, see for example Tsakiris & Haggard, 2005; Costantini & Haggard, 2007).

We have previously argued (see van Dam & Stephens, 2018) that active conditions such as the moving RHI (Tsakiris et al., 2006; Dummer et al., 2009; Newport et al., 2010) or virtual hand illusions (Sanchez-Vives et al., 2010; Shibuya et al., 2018) that use visuomotor congruency, give a stronger or more robust illusion of body ownership, that can incorporate objects that do not look visually similar to the real hand, as long as those are matched spatially and temporally with our felt movements (Dummer et al., 2009) or there is consistent or predictable feedback from the movements (Ma & Hommel, 2015). For example, people have reported ownership of avatars with limbs of a different size (Linkenauger et al., 2013), or completely non-humanoid objects such as a balloon or ball (see Ma & Hommel, 2015; van Dam & Stephens, 2018).

There is an increasing use of gesture-based systems that could employ a 3D cursor that is non-humanoid to represent the movements of the user (Douglas et al., 2018). It is important for tasks and training in VR that they are easy to use and that there is little frustration, but it is unclear what amount of delay would be tolerable. Different people are able to notice differing amounts of delay in a system (Jerald, 2009) and are more sensitive to delays when the direction of movement changes (Jerald, 2012). Long and Gutwin (2019) looked at how different methods of control affected latency, they found that targeting games are affected by latency as low as 41ms. Delays inherent to a system can then be amplified if doing real-time training or tasks over an internet connection, something that companies designing training programmes in VR will need to be able to show won't affect the efficacy of their programmes.

Previous studies often used short VR sessions to test different display conditions, but most real-world VR applications involve longer exposure. Lag caused by slow internet connection or computer processing could vary throughout the exposure. Little attention has been given to how subjective experiences like ownership and agency change with varying amounts of delay, how much can be tolerated, and how this relates to task performance. This study investigated the mapping between the delay, behavioural task performance and the ratings for ownership and agency. In particular we were interested in the degree to which reductions in ratings of ownership and agency with increasing delay were directly related to the increased spatial tracking errors and tracking lags that this introduced.

To do this we measured how the ratings and behavioural task performance varied with increased delay using target-tracking task. The target object was a sphere that moved in three dimensions and participants controlled a second virtual ball to track the target. Delays of 0, 150, 300, 450, 600 or 900 milliseconds between the participants' hand movements and the virtual movements were introduced. No-delay trials were interleaved to avoid potential adaptation effects from influencing the results. After each trial, participants rated their feelings of ownership and agency using a sliding scale, which was presented in the virtual environment.

Skin conductance, or Galvanic Skin Response (GSR) can also be a measure of embodiment in ownership illusions. An autonomic nervous system response is triggered when the embodied fake hand or object is under threat, in anticipation of pain, where increased response is correlated with increased subjective sense of ownership. Having a physiological measure of the extent of the illusion is useful to compare to subjective ratings as the response cannot be faked (Armel & Ramachandran, 2003).

Conditions that manipulate the level of ownership using delays, or even feeling less ownership itself, could increase baseline GSR as they may make it inherently more difficult to complete a task or increase the level of frustration. Increased GSR has been found to be a measure of discomfort (Kamei, 1998) and correlates with other measures of frustration (Bruun et al., 2016). This increase in baseline could then potentially leave less 'room' for a peak during a novel threat. We therefore introduced GSR as a measure to explore if there are baseline changes that may have confounded results from previous embodiment paradigms.

Experiments in previous chapters found that agency was always rated as high, as participants always had the same level of control over their virtual representation. In this experiment, the delay means that actual level of immediate control was decreased so we could find out how this is reflected in the ratings and compare it to task performance.

We expect task performance to be better at delays within the temporal binding window (up to 300ms) as participants would be better able to judge how their movements are affecting the controlled ball.

We also expect the feelings of ownership and agency to be lower with increasing delay, as has been found in previous moving RHI paradigms. We argued that people can feel embodiment over a non-humanoid object if there is a consistent delay, in this paradigm the delay is varied on target trials and may not be adapted to. We expect this to have less of an effect within the temporal binding window, as the outcome can still be used by the predictive internal model.

With increasing task difficulty, we also expect GSR to increase due to the increased levels of frustration with the task.

5.2 Method

5.2.1 Participants

The study was approved by the Ethics Committee of the Department of Psychology at the University of Essex prior to data collection (ethics code: ETH1920-1719). The participants were naive with respect to the purpose of the experiment and informed consent was obtained from each participant on paper prior to the pandemic and then through Qualtrics while restrictions were still in place. The experiment was completed by 18 participants, aged between 18 and 49. Power considerations are included in Appendix A. One participant was left-handed and used the opposite setup to keep the controller in their dominant hand.

5.2.2 Apparatus

The experiment was set up in a similar fashion to van Dam and Stephens (2018).

Participants used an Oculus Rift Head Mounted Display (HMD), along with the Oculus Touch controller corresponding to their dominant hand to interact with the virtual environment.

We created the virtual environment using of the sample code that was included with the Oculus SDK ("OculusRoomTiny_Advanced/ORT (Controllers)") modified for the purpose of the experiment. The virtual room that participants were placed in was 20 by 4 by 40 units in the virtual space (1 unit roughly corresponds to 1 metre in physical space) and the room consisted of 3 walls (at the left, right and back of the participant's starting point), ceiling and a floor. There was a simple grey brick pattern on the walls and ceiling, and a checkerboard pattern on the floor, see figure 5.2.2 below. In the room was a virtual screen (2 by 1 units at 4.5 units distance in front of the participant in the virtual space) where instructions were displayed for the participant to follow. Direct3D was used to render the 3D content of the virtual environment.

Galvanic skin response (GSR) was collected using the Neulog GSR logger sensor (NUL-217, Neulog, 2018). This sensor recorded the GSR in microsiemens and was connected to the PC through the Neulog USB module (USB-200).

Participants were seated in an office type chair with space in front to be able to move their arms freely. For right-handed participants, a table was situated to the left for them to rest their left arm, so that the GSR sensors could be attached to the index and ring finger of the left hand, and the heart rate monitor attached to the middle finger. For left-handed participants the sensors were attached to the right hand.

5.2.3 Stimulus and method

Participants performed a target-tracking task in the virtual environment.

Participants were seated the chair and the GSR and heartrate equipment was fitted to their non-dominant hand. They were asked to sit quietly for 10 minutes to reach rested levels before beginning the experiment and asked to move their non-dominant hand (with attached electrodes) as little as possible during the experiment. They could stop the experiment at any time and could rest between blocks if needed.

Participants were instructed to “Track the green ball as accurately as possible” and pressed “A” on the right-hand controller (“X” on the left-hand controller if left-handed) in order to start each trial. Once the button was pressed, the stimulus was presented.

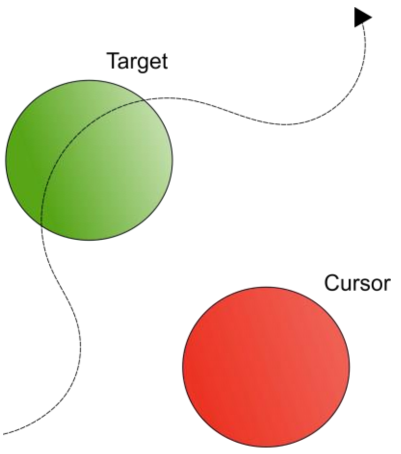

Figure 5.2.1 shows the moving green target ball and the controlled red cursor ball.

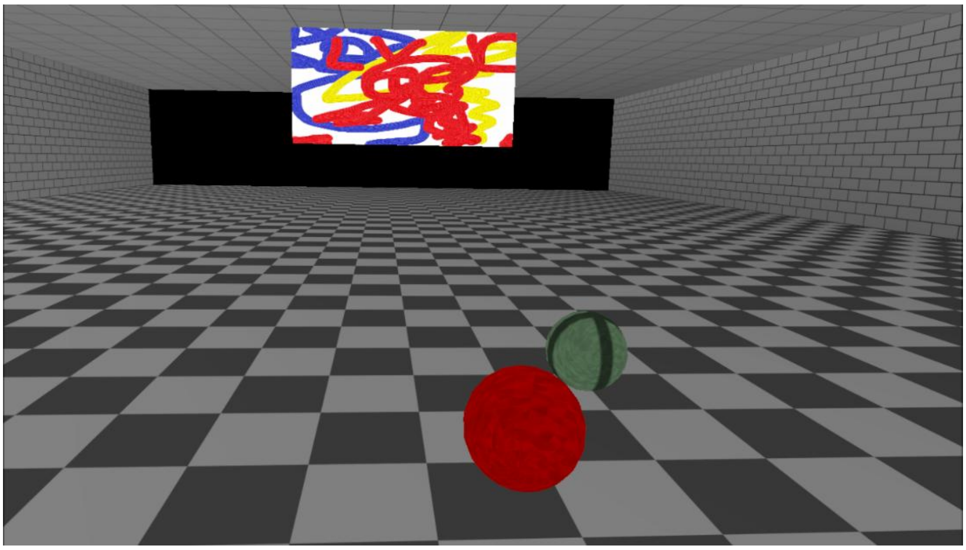

Figure 5.2.2 shows the stimuli in the virtual environment as it was presented to the participants. The central screen acted as a placemarker for the subsequent ratings questions to be displayed.

The stimulus used was the same as in van Dam and Stephens (2018), repeated here for the purpose of completeness. The target stimulus was a green ball with a radius of 5 cm (0.05 units), floating approximately 1 unit above the floor. Its movement was generated by independently combining five sinusoids in the x, y, and z directions. Each sinusoid had a unique frequency and an amplitude of 0.05 units, leading to a potential maximum deviation of 0.25 units in any direction when all sinusoid peaks coincided. The frequencies of the sinusoids were 0.09, 0.165, 0.195, 0.375, and 0.495 Hz (this is depicted in Rohde et al., 2014). The initial phases of each sinusoid were randomly selected from a uniform distribution between 0 and 2π for each trial, with separate random starting phases for the x, y, and z directions.

The participant controlled a red ball of 0.05 units radius in order to track the green target ball for the 10 seconds that made up each trial. In the virtual environment the red cursor ball was continuously being displayed at the location that corresponded to the location of the real dominant hand from the participant's viewpoint as they moved their hand to track the target in conditions where there was no delay. For the conditions with added delay, the ball was displayed at the location corresponding to the real hand 150ms later in the 150ms delay trial, for example. After each trial, participants had to answer on screen questions using a continuous sliding scale as used in van Dam and Stephens (2018).

The continuous scale extended from "not at all" on the left (approximately 1 unit to the left of the centre on the virtual scale, corresponding to a value of -1) to "very much" on the right (about 1 unit to the right of the centre, corresponding to a value of +1). The ownership-related questions were "I felt like the red ball had become part of me" and "I did not know where my actual hand was" (control). The agency-related questions were "I felt I was controlling the red ball" and "The red ball seemed to have a will of its own" (control).

Participants used the thumbstick on the Touch controller to move the marker along the scale, with no additional feedback delay while making these ratings. After positioning the marker to indicate their answer, participants pressed the B button on the right controller (or Y on the left controller). After each question, the marker reset to the centre to minimise the influence of previous answers. Once all four questions were answered, participants could proceed to the next trial.

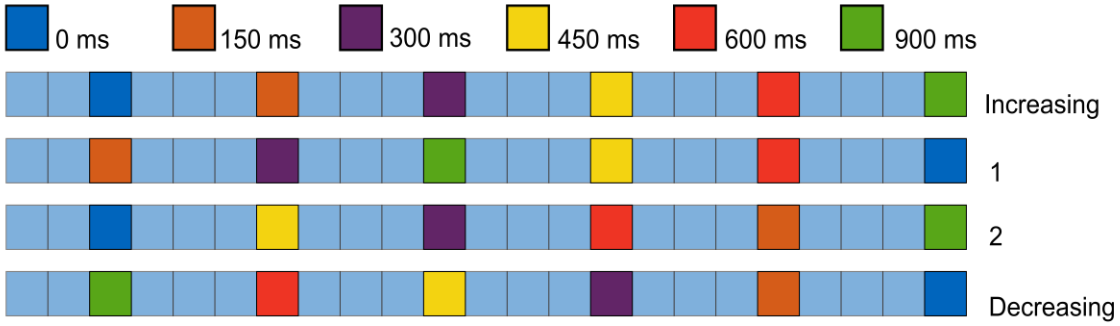

Figure 5.2.3 shows an example trial order. Each participant had an increasing delay block, 2 blocks with the 6 delays in a randomised order, and lastly a decreasing delay block. Light blue shows the 0ms delay trials between each target trial.

Each participant completed four blocks of 23 trials. Trials lasted 10 seconds each and either had no delay, or a delay of 150ms, 300ms, 450ms, 600ms, or 900ms. The first and fourth block were the same for all participants; the first block always had increasing delays and the last always had decreasing delays. The two middle blocks were selected from the 6 orders and counterbalanced across participants. Each target trial was separated by three trials with no delay to avoid potential order effects from influencing the results.

5.2.4 Analysis

On each trial, both the path of the target ball and the path of the cursor ball were recorded to obtain the behavioural measures of adjusting to the added feedback delays. The positions were sampled at 90Hz.

The first two seconds of each trial were removed prior to analysis as this section would be the participant reacting to the target ball's initial position and subsequently catching up with the target ball. The spatial measure was then calculated as the Root Mean Squared (RMS) distance between the target ball and the visual cursor ball within the virtual environment across the duration of each trial, measured in cm.

Additionally, the temporal measure was calculated as the time-lag between the target and cursor paths in the tracking task. As in van Dam & Stephens (2018), the time lag for each trial was determined using a cross-correlation method on the target path and the path that is taken by the real hand, plus the delay.. This method calculates the correlation coefficients between the target and cursor paths by shifting one of them back and forth in time relative to the other. The time-shift that results in the highest correlation indicates the time lag between the two signals. The cross-correlation was performed separately for the x, y, and z directions, resulting in correlation coefficients as a function of time shift for each dimension. These coefficients were then averaged across the three dimensions to find the time shift that maximized the correlation between the target and cursor paths. This shift represents the lag between the target and cursor and will be referred to as the lag measure in the tracking task, expressed in seconds.

The repeated measures correlations between the behavioural measures (task performance in spatial error and visual lag) and subjective ratings were calculated using rmcorr in R (Backdash & Marusich, 2017).

5.2.5 Galvanic Skin Response analysis

The data was trimmed to include only the time range between 500 and 9800 milliseconds. This was done to focus on the relevant part of the data and exclude the initial and final parts that might be less relevant or noisy.

A low-pass Gaussian filter (sigma value 500) was applied to the skin conductance data (the filter was normalised by dividing by the sum of its values to ensure that the total weight is 1 to avoid changing the overall signal magnitude). The data was then detrended by subtracting the filtered signal and the mean skin conductance from the raw data to eliminate general non-task related trends. The detrended data was then normalised to a range of 0 to 1 so it could be compared across trials and participants.

The GSR increase for the delay trials was calculated by subtracting the GSR of the first 0.5 seconds from the GSR of the last 0.5 seconds. We also considered the GSR increase for the trial directly after the delay trial as the response can take up to 10 seconds (Bruun et al., 2016). This does mean that due to the experimental design there would have been trials that were not included, as they were the last trial in the block. The middle two blocks were counterbalanced so that trials with missing values due to this would be spread across delays. Sphericity was calculated using a Mauchly’s test using IBM SPSS Statistics (Version 27, IBM Corp., 2020) before repeated measures ANOVAs were conducted using RMAOV1 in Matlab (Hernandez-Walls, 2004).

The analysis was not pre-registered.

5.3 Results

5.3.1 Behavioural Results

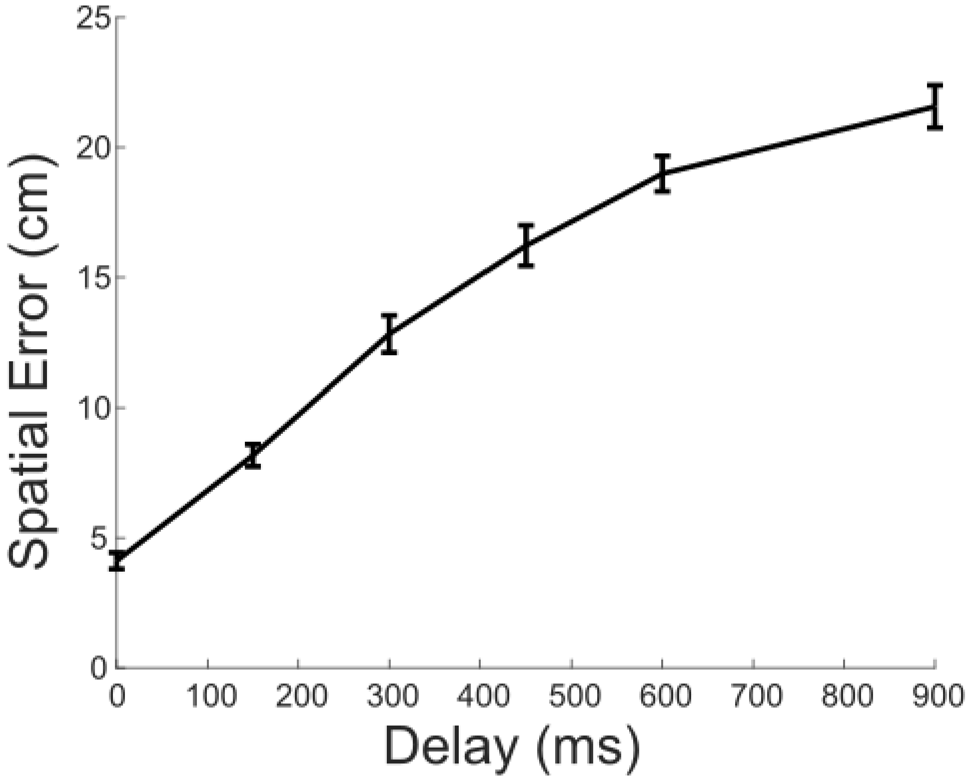

Figure 5.3.1 shows the RMS of the distance between controlled ball and target as the spatial error at different delays. Error bars show standard error.

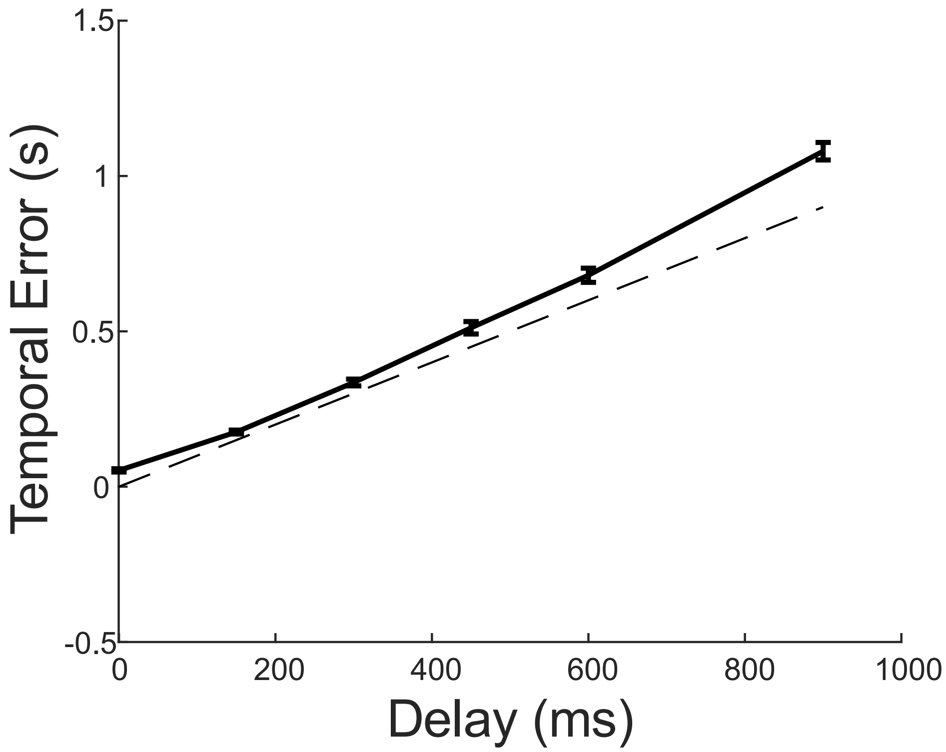

Figure 5.3.2 shows the visual lag between the controlled ball and target as the temporal error at different delays. The dotted line represents a slope of 1. Error bars show standard error.

Participant task performance was analysed to see how the delay between participant movement and the movement of the on-screen representation affected their behaviour in the virtual environment. Two dimensions of task performance were considered: spatial error (how far participants were away from the target ball throughout the trial, calculated as the RMSE in cm); and temporal error (how far behind in time the controlled ball was from the target ball along the path it took, in seconds). We expected task performance to be better at delays within the temporal binding window (up to 300ms).

A repeated measures ANOVA found that participants perform worse at the tracking task with increased delays, both in the spatial ($F(5,85) = 244.99$; $p < .001$) and temporal sense ($F(5,85) = 660.54$; $p < .001$). With increased delays, the visual cursor that participants controlled was both further away from the target ball and lagging further behind it. This was more pronounced at delays of 900ms (see figure 5.3.2). This delay condition was far outside the temporal binding window and shows that some participants may have felt unable to complete the task and given up during the larger delays, some comments are noted when looking at the subjective ratings.

5.3.2 Rating results

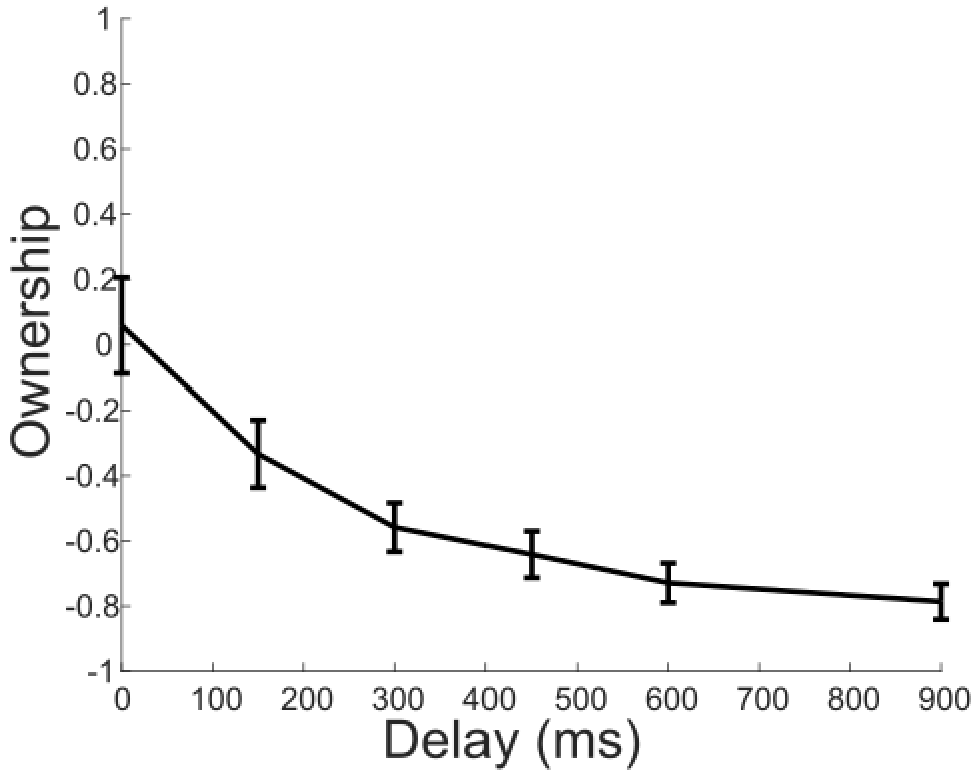

Figure 5.3.3 shows the rating results for ownership averaged across each delay. Error bars show standard error.

After each trial, participants were asked to rate their subjective feelings of ownership and agency over the avatar movements. The rating scales went from -1 (Not at all) to 1 (Very much), with 0 being a neutral or ambivalent response. We expected the feelings of ownership and agency to be lower with increasing delay. We also expected this to have less of an effect within the temporal binding window.

Participants felt more strongly that the red ball had become part of them at smaller delays (Friedman $\chi^2(5)= 51.36$; $p < .001$) but this was close to neutral for 0ms delays and got closer to 'not at all' with increasing delays, meaning that participants did not get the feeling that the ball had become part of them.

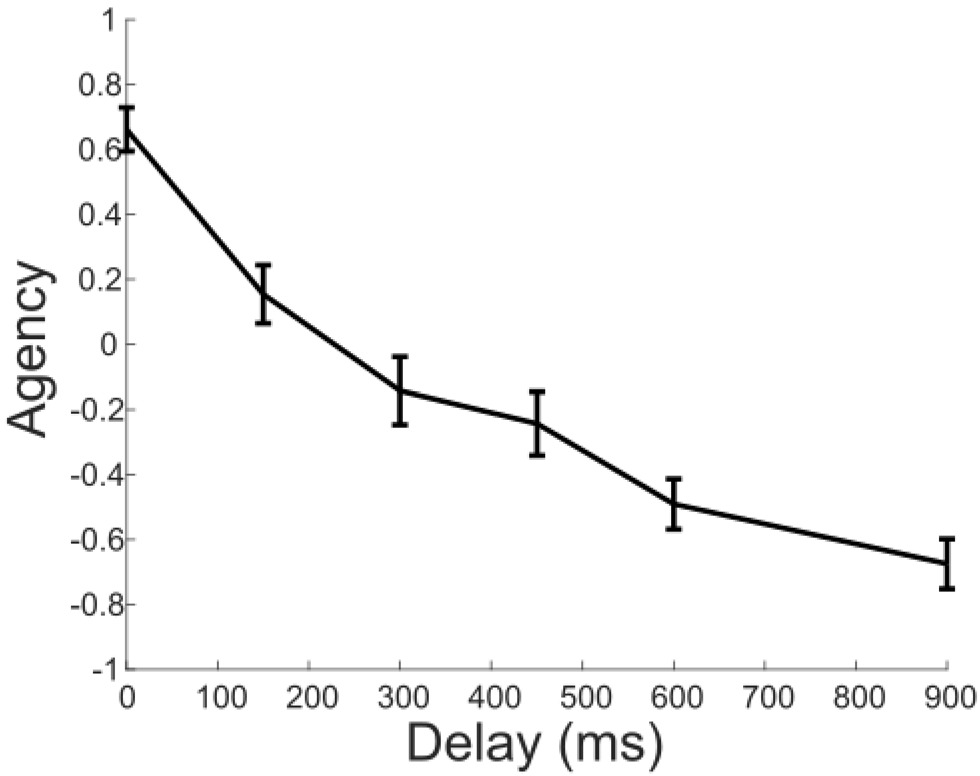

Figure 5.3.4 shows the rating results for ownership averaged across each delay. Error bars show standard error.

Participants felt more in control of the red ball at smaller delays (Friedman $\chi^2(5)= 82.16$; $p < .001$.)

To ensure that participants weren't clicking one end of the scale for every question, they were asked to rate the statements 'I did not know where my actual hand was' as a reverse coded ownership control question and ‘The ball had a will of its own’ as a reverse coded control question for agency.

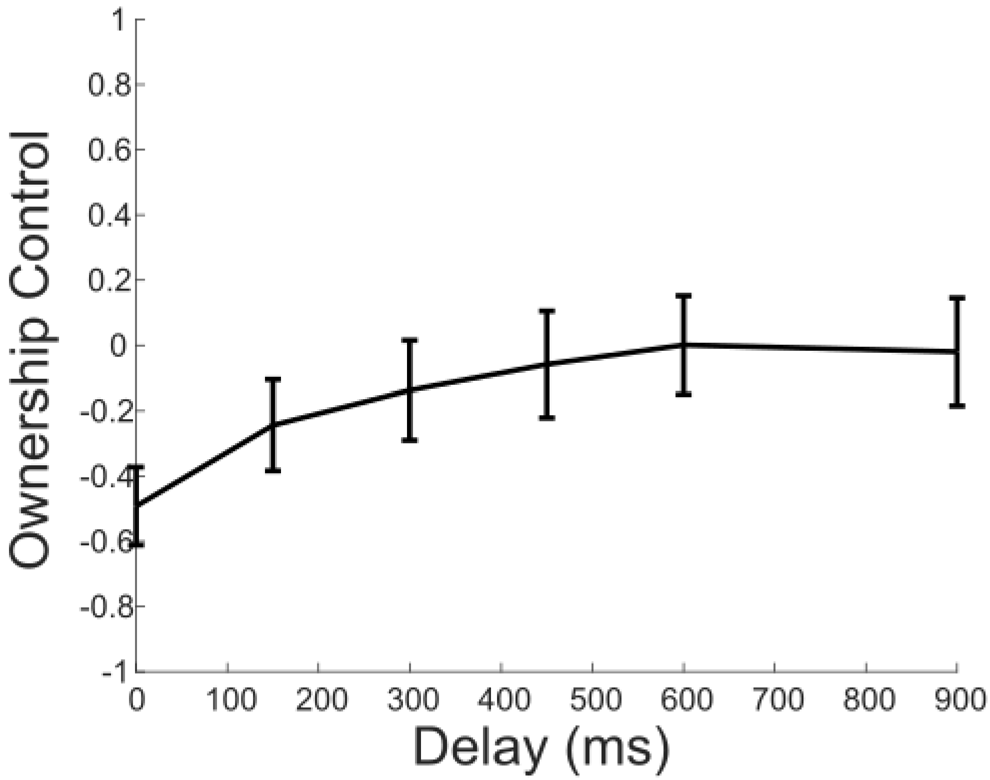

Figure 5.3.5 shows the rating results for the ownership control question averaged across each delay. Error bars show standard error.

The ownership control ratings differed significantly across delays (Friedman $\chi^2(5) = 18.24$; $p = .003$). Participants felt that they didn’t know where their actual hand was more as the delays increased.

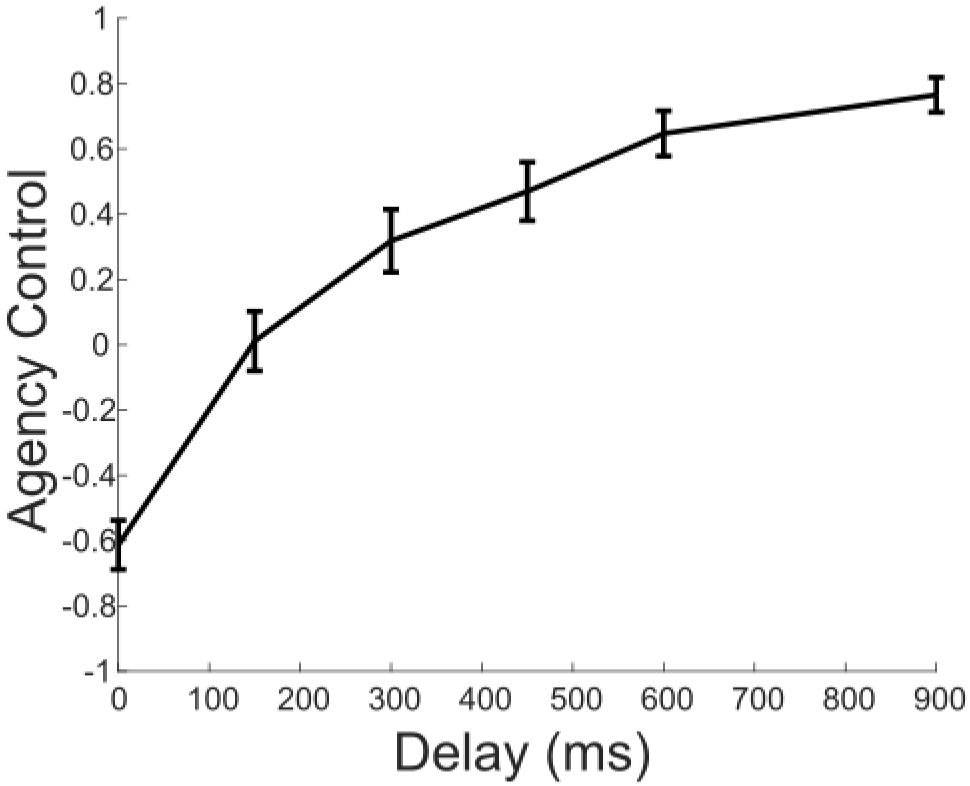

Figure 5.3.6 showing the rating results for the agency control question averaged across each delay. Error bars show standard error.

This agency control ratings also differed significantly across delays (Friedman $\chi^2(5)= 81.56$; $p < .001$), with participants feeling more strongly that the ball was not under their control for delays above 150ms, as if it had been programmed to move by itself.

With increasing delay, participants reported that they were less in control of the ball, as if it had been programmed to move by itself. During the experiment it was noted that some participants during the 900ms trials reported that they didn’t feel as though they were controlling the ball at all, even though their movements were the only thing that caused it to move.

5.3.3 Repeated measures correlations

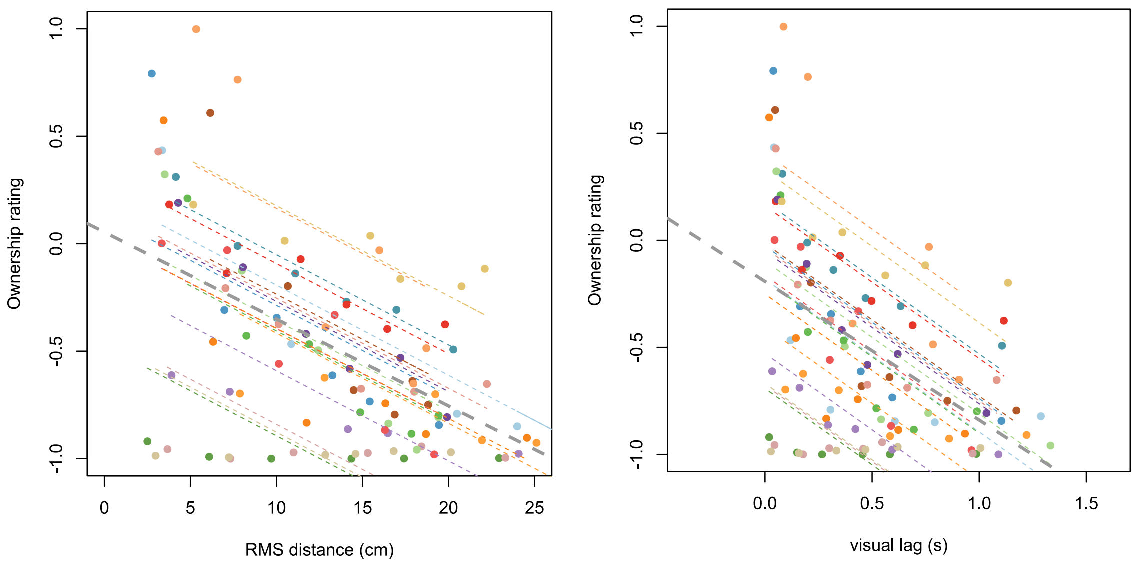

Figure 5.3.7 showing the repeated measures correlations using rmcorr for both spatial error (RMS distance) and temporal error (visual lag) against the ratings for ownership. Observations from the same participant are given the same colour, with corresponding lines to show the rmcorr fit for each participant. The dotted grey line shows the average across participants.

The correlation coefficient was calculated to assess the linear relationship between the RMS distance of the controlled ball to the target ball and the ratings for ownership. There was a negative correlation between the two variables, rrm(89) = -0.73, $p < .001$ 95% CI [-0.81 -0.61].

The relationship between visual lag and the ratings for ownership was then calculated. There was a negative correlation between the two variables, rrm(89) = -0.68, $p < .001$ 95% CI [-0.78, -0.55].

This means that participants felt decreasing ownership over the controlled ball the worse their task performance was both in terms of distance from the target ball and the lag behind it on the target path.

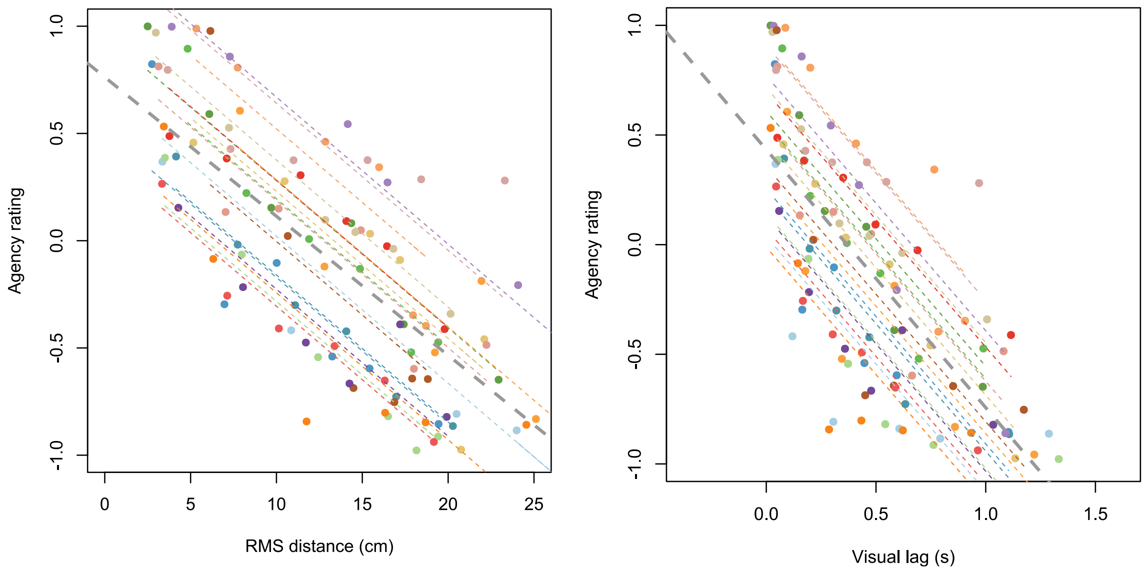

Figure 5.3.8 showing the repeated measures correlations using rmcorr for both spatial error (RMS distance) and temporal error (visual lag) against the ratings for agency. Observations from the same participant are given the same colour, with corresponding lines to show the rmcorr fit for each participant. The dotted grey line shows the average across participants.

The correlation coefficient was then calculated to assess the linear relationship between the RMS distance of the controlled ball to the target ball and the ratings for agency. There was a negative correlation between the two variables, rrm(89) = -0.90, $p < .001$ 95% CI [-0.94, -0.86].

The relationship between visual lag and the ratings for agency was then calculated. There was a negative correlation between the two variables, rrm(89) = -0.84, $p < .001$ 95% CI [-0.90, -0.77].

The negative correlations mean that the further the participant was from the target ball both spatially and in terms of time, the less they felt like they were in control of it.

<u>5.3.4 GSR results</u>

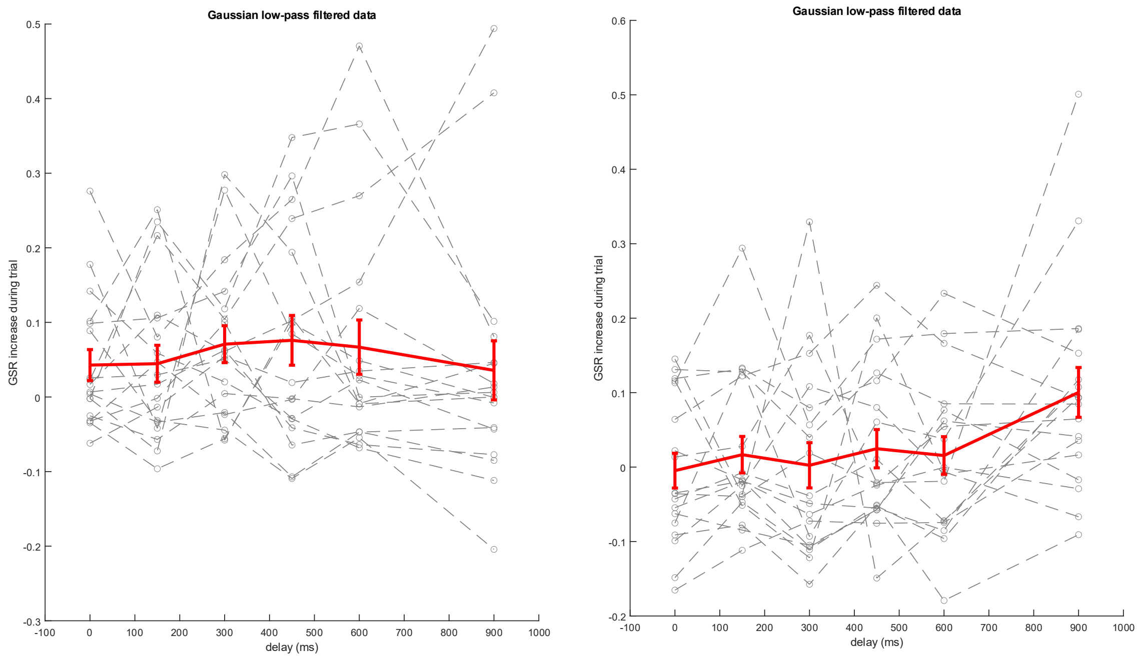

Figure 5.3.9 showing the GSR increase during the delay trial on the left, and the trial following the delay trial, on the right.

With increasing task difficulty, we expected GSR to increase due to the increased levels of frustration with the task. Mauchly's test of sphericity was non-significant ($p = .217$), so we used a standard ANOVA to see if there was a difference in GSR for different delays. When looking at the GSR increase during the target trials, there was no significant difference between the different delays ($F(5,85) = 0.49$, $p = .786$).

We also looked at the GSR increase for the trial directly after the target trial, as it has been found that there can be up to 10 s of lag in the GSR measure (Bruun et al., 2016). A one-way repeated measures ANOVA revealed that there was a significant difference between trials after different delays ($F(5,85) = 2.99$, $p = .016$). Post-hoc t-tests revealed that the trials directly after the 900ms delay trial had significantly more GSR increase than trials with less delay (e.g. for 600ms $t(17) = 2.21$, $p = .021$).

There were no differences between any of the other trials immediately after a delay trial.

The results show that with increasing delay both spatial tracking error and tracking lag increased as expected (i.e., task performance decreased). In a similar fashion, the ratings for ownership and agency decreased with increased delay and were both negatively correlated with the spatial tracking error and tracking lag. These results indicate that task performance and subjective ratings are similarly affected by the delay. The GSR results suggest that there is a lag in GSR response to frustration and that tasks with 900ms delay are significantly more uncomfortable or frustrating than tasks even at 600ms.

5.4 Discussion

This study investigated the mapping between movement delay, behavioural task performance and the ratings for ownership and agency. We were interested in the degree to which reductions in ratings of ownership and agency with increasing delay were directly related to the increased spatial tracking errors and tracking lags that this introduced.

We first found that both spatial tracking error and tracking lag increased with increasing delay. Ratings for ownership and agency also decreased significantly with increased delay and were both negatively correlated with the spatial tracking error and tracking lag. These results indicate that task performance and subjective ratings are similarly affected by the delay.

With increasing delay, participants reported that they felt less in control of the ball, as if it had been programmed to move by itself. During the experiment it was noted that some participants exclaimed during the 900ms trials, with some reporting that they didn’t feel as though they were controlling the ball at all, even though their movements were the only thing that caused it to move.

There was more of a change in the subjective feeling of agency across delays and a much clearer relationship between agency and task performance, in comparison to ownership. It could be that the feeling of ownership is more dependent on the appearance of the virtual representation. We argued that the visuomotor congruency would be stronger than visuo-tactile stimulation for the illusion because the movements are internally generated. It has been found that people need only a small number of trials with visuo-motor feedback in order to adapt to a change in what is expected (Martin et al., 1996) and that delays in a target tracking task can be adapted to, increasing ownership ratings as adaptation occurs (van Dam & Stephens, 2018), however these changes need to be predictable and repeated. It has been found that having a visual cue of the delay can reduce its effects (Gutwin et al., 2004) as a strategy to overcome the delay is predicting and leading the target movement (Long & Gutwin, 2019; see also van Dam, Nilsen, & Stephens, 2021). However, since this adaptation relies on predictability, we didn't see this in the current task, as the delays were randomised and had trials without delay in between so that any aftereffects wouldn't impact subsequent trials. Since network latency is often not uniform, this suggests the importance of incorporating something that provides a visual representation of current delay so that users can make adjustments to their movements accordingly.

The ratings for the sense of ownership are just above neutral, participants did not feel strongly either way that the red ball had become part of them at 0ms delay. Although this would suggest that the illusory sense of ownership was not induced over the controlled ball, the ratings did significantly differ across delays; with increasing delay participants increasingly rejected the notion that the ball had become part of them. This also could explain the weaker correlations with ownership and behavioural measures, as there is less 'room' for the feeling to reduce as task performance reduced. The feeling of ownership is hard to define in comparison to the feeling of agency. The term "ownership" or something to feel a part of you is open to different interpretations by the participants. So it could be that different participants based their response on (partially) different heuristics (see for example Slater, 2004), which may also be based on task-performance. We argued for a 'fuzzy' sense of ownership that can incorporate other, non-humanoid objects, but it could have been unclear to participants what it means for something to be part of their body. The results suggest that the feeling of ownership over a virtual representation is more affected by its appearance, rather than the feeling of agency which is driven more by the seen effects of intended movement.

The higher agency ratings compared to the ownership ratings could suggest that the controlled ball, even though it did not have an associated virtual hand to ‘hold’ it, was seen as a tool for the job of tracking the target ball. While tools can act as sensory extensions of the body rather than just links to far away objects (Miller et al., 2018), Osiurak and Federico (2021 p.3860) argue that this embodiment of a tool is an “action-oriented form of incorporation” meaning that we are focusing on what the active part of the tool can achieve, with the feedback giving a sense of agency over the movements. Miller and colleagues (2014) also found that tools that are more similar in appearance to the part of the body they represent are more readily embodied.

It could that the reported feelings of ownership and agency were a result of suggestion (Lush, 2020) with participants guessing the anticipated results of both the illusion and control questions. If this was the case, we would expect the agency ratings to be reported at a similar level to the ownership ratings. As discussed, however, participants may have understood what the agency questions were asking better than they understood the ownership questions.

In this experiment, we also measured the GSR to assess how baseline measures could be affected by changes in task difficulty. When looking at the increase in GSR during delay trials, although not significant, there was a slight increase in skin conductivity for trials with delays around the temporal binding window. This could affect calculations using baseline GSR when considering threat conditions, as increased frustration could increase baseline and there could be a ceiling effect.

Due to the lag in skin conductance increase (Bruun et al., 2016), which can be longer when using dry electrodes such as those used by the Neulog sensor (Higashi, Yokota, & Naruse, 2017; Flagler et al., 2020) we also looked at the trial directly after the delay trials and found that there was a significant increase in GSR for 900ms trials. Since this was not accounted for prior to data collection, it means that some trial data was missing, i.e. the 900ms trials in the first block, the 0ms trials in the final block and counterbalanced delay trials in the middle two blocks, due to the counterbalancing this should not have affected the results. This increase to the baseline, even when no threat conditions were introduced, needs to be taken into account when considering novel ways of breaking the sense of ownership. It was also interesting that there was no significant increase at 600ms, which is outside of temporal binding window, however. This could mean that delay can be used without significantly increasing frustration while still reducing the illusory sense of ownership.

Other studies have found that the lag in stimulus and GSR is only 1-3 seconds (Surwillo & Quilter, 1965). This increase, therefore, could also be a reaction to the delay returning to 0ms, and could be a sign of relief, as positive emotions can also increase skin conductance (Paul et al., 2020).

Flagler and colleagues (2020) recommended that the Neulog electrodes be attached for 5 minutes before the experiment started in order to stabilise readings. Even though we did this as part of the experimental design, many participants' GSR had a downward trend throughout the experiment, even after 45 minutes. This could have been caused by participants having had to walk to the lab where the experiment was conducted, or nerves about taking part in the experiment, and suggests that 5 minutes of wait time was not sufficient.

A second recommendation was that the Neulog GSR device not be used if the participant is required to make movements with the hand that the sensors are attached to, as this creates artifacts (Flagler et al., 2020). Participants were instructed to keep their hand with the attached electrodes as still as possible, but some participants required reminding of this, especially at longer delays where the task was more difficult.

VR is being increasingly used for training and teleoperations (Xie et al., 2021; Cesari et al., 2024), therefore investigating the effect of delay on the feelings of ownership and agency, as well as task performance, is becoming vitally important to give us a better understanding of how professionals can cope in teleoperator settings, where delays might vary and be inherent to the setup.

Chapter 6: Discussion

This thesis aimed to explore the effect of avatar and tool appearance on ownership and agency during virtual tasks. In order to do this, we asked participants to perform tasks using virtual tools that represent real-world movements and changed the appearance and behaviour of these tools to see if this in turn changed user behaviour in the tasks, such as task performance, along with the reported feelings of ownership and agency.

The first two experiments considered the visual characteristics of computer cursors and how they would have an effect on pointing behaviour and the feeling of agency over the movements. To do this, in the first task participants performed a target pointing task with an arrow shaped cursor and a hand shaped cursor presented at four orientations. It was found that participants felt the most agency towards the more familiar arrow cursor pointing to the top left. The level of familiarity of the arrow cursor was significantly affected by orientation, but this was not the case for the hand cursor. Fastest completion times were also found at familiar cursor rotations and there was more deviation from a straight path to targets orthogonal to cursor orientation for both cursors, with the arrow cursor being more affected by orientation.

The next task looked at cursor size with the same paradigm using arrow shaped cursors at two sizes and with four orientations. This experiment also showed that the feelings of agency and naturalness were higher overall for the small cursor and was strongest for the small cursor in the most familiar orientation. Completion times were also significantly faster with the cursor pointing top-left, with the larger cursor having longer completion times for movements that were backwards along the path to the target. Movement paths were curved in cases where the pointing direction was orthogonal to the cursor orientation. These curvatures were more pronounced for large cursors. These results show that even in a simple pointing task, cursor appearance and familiarity affect both pointing behaviour and the feeling of agency.

The next experiment aimed to see whether tool (virtual hand) size had an effect on pointing behaviour in a pointing task in a virtual environment. Participants were in control of a realistically shaped virtual hand that was either matched in size to their real hand, 50% of the size or 200% of the size. Participants were able to become embodied to the hand during the starting phase where the fingers matched their movements on the controller, and they had to move their hand into the starting sphere. The hand was then hidden for the reaching phase. Results showed no change in pointing behaviour for the different hand sizes, and no change in the sense of agency over the movements. However, participants felt more ownership over the size-matched hand. This shows that tool size does affect the feeling of ownership, but that the sense of agency was not similarly affected.

The final experiment considered whether reducing the synchronicity between felt and seen movements affected ownership and agency in a virtual tracking task. By introducing delays, we hoped to see if there was a systematic relation between task performance at different delays and the subjective ratings of ownership and agency. We found that increasing delay increased spatial and temporal errors, and that task performance in both spatial and temporal terms positively correlated with the feelings of ownership and agency. Agency and the spatial component of task performance had the highest correlation. However, ownership was generally rated low even though it continued to diminish with increasing delay.

This experiment also demonstrated that the 900ms delay condition, intended to manipulate the level of ownership and agency, also increased the skin conductance in the subsequent trials.

6.1 Ownership

The general trend that we found across the VR based experiments was that the sense of ownership was highest when the controlled representation looks the most like the actual hand, and when it synchronously matches the movements (without any added delay). This is what we would expect from previous literature that found that ownership is more dependent on the appearance of the tool (for example see Ratcliffe & Newport, 2017).

In our studies, visual cues were disrupted, while other cues (such as proprioception) were not. Our results therefore show that visual cues contribute to the feeling of ownership and quantify how this is reduced by a changed mapping of scale or timing between visual and proprioceptive cues.

It is believed that active movement conditions produce a stronger form of the RHI (Dummer et al., 2009; Ma & Hommel, 2015), such that non-humanoid objects such as tools could be incorporated in this case. However, for the VR tracking experiment the delays were interleaved so that no adaptation would take place. The reaching experiment with varied hand size did have consistent hand sizes within a block, but there was no feedback on the movements (participants did not see the hand during pointing) that could provide a calibration signal. This could mean that the internal schema for motor movements would not have been able to integrate these changes.

Ma and Hommel (2015) found that non-corporeal objects such as a balloon can be perceived as body parts as long as their changes are related systematically to the movements made by the participant. The delay trials we introduced meant that it was harder to see that the movements were related. In addition to moving synchronously, the balloon used by Ma and Hommel (2015) also changed with finger movements, becoming larger with the opening of the hand and smaller when closing the hand. These matches in finger movements could have produced stronger feedback that can be used to update the internal representation of the body. The controlled ball in our experiment only had the global hand movement that was tracked by the controller, with no visual characteristics that could represent finger movement.

The generally low ownership ratings that we observed for the non-humanoid tool were also found in Ma and Hommel's (2015) experiment, however. They suggest that the disconnect between the representation and the body is behind this low rating. It has been found in virtual hand illusion paradigms that the illusion relies on the virtual object appearing to be connected to the body of the participant (Perez-Marcos et al., 2012).

Although in our experiment there was no virtual representation of the hand to hold the controlled ball, it is likely to be seen as a tool that is being controlled, which is less constrained by top-down visual expectations, as it extends the body without being part of the body.

It could be that more training in the no delay condition before the target trials could have increased the sense of ownership just by participants becoming more familiar with the tool. In a delay adaptation task, it was found that subjective ratings continue to improve even in unpredictable conditions where temporal adaptation cannot take place (van Dam, Nilsen & Stephens, 2021), suggesting the importance of familiarity with the representation. Perhaps more training in the no delay condition would increase ownership as the internal representation would update, thus allowing us to become one with the tool (Biggio et al., 2020). Our experiment did have conditions without delay between target trials, however this may not have been enough to build this sense of familiarity as it was broken by the delay conditions.

The difference in ownership scores between the experiments, with the hand representation being scored relatively high in the reaching task compared to the ball (scored close to neutral even in the no delay trials), does suggest an importance of the representation being visually similar to the real hand even in active movement conditions. In both cases the virtual representations were disconnected from the body, which has been suggested to reduce the sense of ownership (Ma & Hommel, 2015).

In the hand reaching task in chapter 4, participants trained with the size-matched hand, which could have increased the familiarity with that size in the context of the virtual environment. Even with less exposure to the virtual representation, in comparison to the tracking task in chapter 5 as the hand was only visible during the starting sphere phase, more ownership was felt over the realistic hand representation, and this was most for the size-matched hand which participants would be most familiar with. It is not possible to directly compare results for hand and ball representations, as these were used in separate studies. However, these apparent differences are suggestive of an effect of using hand-like stimuli for increasing ownership, which could be followed up in future studies. Again, this strongly suggests the top-down constraints of expected visual appearance of the representation play a huge part even in the active movement conditions. It would be interesting to see in further studies if there is a difference if participants were trained with the smaller or larger hand instead, and whether they used that as their familiarity benchmark rather than in comparison to the size of the real-world hand, which has been shown to be inaccurately represented in the brain in terms of size and shape (Linkenauger et al., 2015b).

These findings suggest that there are a few key attributes that affect the feeling of ownership. Firstly, there is appearance, how much the tool looks like the relevant body part, rather than a simple object such as a ball. Then there is active control and the complexity thereof, for example my experiments considered movement but more complex experiments where finger movement also provides greater dimensionality to the extent that the object is under the person's control (such as in Ma & Hommel, 2015). There is also connectedness, the extent to which the tool appears physically connected to the body. These attributes provide evidence that an external object belongs to us. Conversely, any evidence that makes us doubt ownership, such as a hand being presented at an incongruent angle, will reduce it.

In the traditional RHI, the synchronous tactile stimulation could be seen as similar to tool use, where the sensations can be felt through the tool, but it feels as though they are coming directly from the tip of the tool, rather than through the fingers holding it (Maravita et al., 2002; Weser et al., 2017). It is possible therefore that the RHI is not showing that the fake hand has been incorporated into the body model, but rather the more malleable body schema is updating to include the tool for future action. In Lewis and Lloyd's (2010) study, participants reported that they felt they could move the rubber hand if they wanted to. If participants are feeling ownership over a tool rather than incorporating a limb, it therefore makes sense that active movement conditions have also found stronger ownership illusions.

GSR has been related to the feeling of ownership, specifically when a threat is made to the fake representation of the hand (for example see Armel & Ramachandran, 2003). While we did not measure a response to a threat condition, the increase in skin conductance in the trial after the 900ms trial suggests that there may be an effect caused by conditions that reduce ownership, that may also increase the baseline skin conductance. The difference in expected movements and seen movements in the virtual world could be considered a surprise to participants. Relating to the bottom-up theory of the RHI, Apps and Tsakiris (2014) describe bottom-up stimuli as ‘surprise’ stimuli and suggest that the internal model acts to reduce the surprise. GSR also measures surprise responses so it could be increased by this mismatch, perhaps reducing the amount that GSR can peak.

Further studies would have explored these skin conductance increases when a threat is presented to the controlled ball. It has also been suggested that the response to a threat may occur independently of body ownership (Ma & Hommel, 2013) and that people can react to a threat to another person in a comparable way to how they would react to the threat being directed towards themselves (see for example Morrison et al., 2004).

There have been instances when the illusion of ownership has occurred even though the visuotactile sensations were asynchronous, for example when the fake body is realistic and superimposed on its real counterpart (Kilteni et al., 2015). This means that synchronous stimulation may not be needed for the illusion to take place under certain conditions. First person perspective has been shown to be enough to induce the sense of illusory ownership. In Slater et al. (2010), male participants felt ownership over a female body when they were able to see it from the first-person perspective in VR, as well as conditions of synchronous movement. This was measured by both a subjective questionnaire and heart rate deceleration during a threat scenario, showing that visuotactile synchrony is not necessary for the illusion.

The reason behind this feeling of ownership over a realistic hand or body, even in the absence of synchronous stimulation, is thought to be part of the neural basis of empathy. We often mirror the bodily states of others, in order to understand their motivations and actions, which Maister and colleagues (2015) believe shows that the representation of our own body can overlap with that of others. It has been thought that this can only occur when the avatar was still that of a human and that the illusion may not be resistant to more drastic changes (Slater et al., 2010). However, humans have a tendency to anthropomorphise various objects, especially if they are moving in a congruent way. Heider and Simmel (1944) showed that a video depicting a collection of simple shapes (triangles and circles moving in and around a square 'house') could elicit responses from observers who attributed complex motivations and intentions to those shapes (see also Castelli et al., 2013).

Further, in Sforza and colleagues' (2010) "Enfacement" experiments, where subjects' faces received synchronous tactile stimulation with touches on a partner's face to induce the illusion that the partner's facial features were being combined with those of their own face. They found that this enfacement was positively correlated with the participants' empathetic traits. Therefore, it is possible that familiarity with the virtual representation and its movements could have driven an empathy related skin conductance response towards a balloon threatened with a needle, as found in Ma and Hommel (2015).

It has therefore been suggested that a neutral stimulus aimed at the embodied virtual representation, such as a non-painful impact from a ball, should be used as this is less likely to provoke the empathetic response (Ma & Hommel, 2013).

We previously argued that active movement conditions are stronger so that non-humanoid tools can also be incorporated into the more stable body model to induce the sense of ownership. Our results instead suggested that the visual characteristics of the virtual tool are important. Previous GSR results (such as those found by Ma & Hommel, 2015) suggest these non-humanoid tools could be incorporated as shown by increased threat response. However, this response could also be caused by the increased salience of the stimuli in synchronous active movement conditions, as there is increased processing around the tool due to expansion of the PPS (Gozli & Brown, 2011), especially in goal-oriented movements (Farnè et al., 2005), but this is not the same as body ownership.

6.2 Agency

The reported sense of agency is generally high over all experiments. This was true both when the representation was a simple cursor on a computer screen, and a 3D object in immersive virtual reality. When the level of control was reduced, by adding delays to movements that participants could not predict or adapt to, we showed that agency is more affected than when simply changing the appearance of the tool (avatar or cursor), as we would expect.

Agency seems to be affected by task performance in the VR tracking task, as suggested by the correlations in chapter 5. This is particularly strong when considering the performance in a spatial sense, there was a higher correlation between agency and spatial lag, rather than temporal lag. It was easier for participants to see how well they are performing in relation to how far away they were from the ball, rather than trying to calculate how far back in time they were along the target path. This could have affected the agency results in different ways. One interpretation could be that the spatial error was providing more reliable feedback, allowing the schema to update and informing the implicit feeling of agency. Another interpretation is that participants would have been able to tell how well they are doing consciously, and were making more explicit judgements of agency based on that, which could also have been influenced by demand characteristics, as discussed below.

Agency was not found to be higher for the size-matched hands in the VR pointing task in chapter 4. This could have been because participants did not get feedback on their performance, the target disappeared whether it was directly hit or not, with no movement to visibly attribute to this outcome. Proprioceptive information alone is not enough to signal our limb's absolute location in space (Longo et al., 2010), we therefore rely on vision to confirm task accuracy. The only multi-sensory cue for agency available in the experiment, therefore, would have been the hand and finger movement in the starting orb phase which did not influence the environment.

In contrast to the VR pointing task, in the 2D cursor pointing tasks the agency ratings were highest when using the cursor that was most similar to the one that participants were used to, the small arrow shaped cursor pointing to the top left. By itself, this finding could suggest that we already have a representation of this tool in our schema for action or goal directed behaviours. When taken with the VR results, it also suggests that feedback is necessary for the explicit sense of agency in goal-directed movements, as participants may have been able to tell that they had improved performance with cursors at the familiar rotation.

In the VR pointing task, participants may have also realised that their pointing performance did not differ between hand sizes, although this is unlikely without any visual feedback. More likely, the agency ratings did not change between hand sizes because there may have been a realisation that the task was not made more difficult as the movements in the virtual environment always matched the real-world movements. Participants therefore did not have to make any adjustments to their pointing behaviour to compensate for changed hand size. Previous literature has also suggested that agency is influenced by synchrony of the motor action, in comparison to ownership being more related to the appearance of the tool (Ratcliffe & Newport, 2017).

An interesting difference between the cursor pointing experiments in chapters 2 and 3 was that for the control question, “The cursor seemed to have a will of its own”. Responses differed across cursor sizes in chapter 3, which was not found for the cursor images in chapter 2, or what we expected as the on-screen movements matched the mouse movements in the same way across both experiments. Participants felt that the large cursor was less under their control, suggesting that appearance also affected agency.

The larger appearance could have changed expectations about the way the cursor should have behaved, so that the internal schema was incorrectly updated. For example, due to the size-weight illusion, participants could have expected the larger cursor to be harder to move and compensated for that unnecessarily, meaning that the movements would violate the expectations of the internal model and reducing agency. This also suggests that it is not familiarity with the tool that is driving the differences in the sense of agency by itself but rather expectations of how a tool should behave.

6.3 Demand characteristics

Our explicit measures of ownership and agency relied on subjective judgements on a rating scale after each trial, or set of trials. Slater (2004) has shown that participants will produce seemingly reliable questionnaire results based on an entirely invented feeling. Participants were asked to rate the colourfulness of their experience of the previous day, along with the extent to which they accomplished their tasks. They found an association with having a good, pleasant, not frustrating day with it being colourful, and to get this you needed to have achieved the tasks you set out to do. While it can be argued that colourful has its own connotations, with bright and more saturated colours associated with joy (Dael et al., 2016), at the time they were completing the tasks participants would not have been making an association with colourfulness. With rating questions, the participants can provide responses on a different metric that seems to fit the ambiguous term used. Participants could have been feeling something else but “the only available linguistic category was indeed used to classify an experience” (Slater, 2004, p.492).

In his paper, Slater (2004) is considering the feeling of ‘presence’ in virtual environments, the sense of being ‘there’ in the environment which includes elements of avatar ownership. Through head tracking, the synchronous movements and sensory information means that what people see in VR are to an extent overriding the real world. People know cognitively that they are not really there in the virtual world, similar to in the RHI they know that the rubber hand is not really their hand. How to quantify this feeling of presence has the same problems as for ownership, it is hard to define in a way that others would understand it. There may be a perceived association with the wording of the rating statements, and participants may be tapping into some other sensations relating to their hand. This may also explain why, although the rating for ownership over the controlled ball in the tracking task was neutral, this continued to decrease with increasing delay.

In the RHI, we know from the start that the fake hand does not belong to us, and yet the illusion happens anyway. This illusion provides a phenomenological experience for which the words ownership and embodiment have been given to us in an attempt to verbally express that feeling. The problem here could be that the provided questionnaires or rating statements are offering these words to describe the feeling that the participants have, but these might not be the right words, especially considering the individual differences in experiencing the illusion (see for example Haans et al., 2012). The participants agree because they have no other way to express it. Longo and colleagues (2008) used phrases from freely reported experiences from 5 participants during the RHI to inform their rating statements in latter experiments, and from these proposed three aspects of embodiment: co-location, agency, and ownership. While agency is arguably easy to define in a way participants understand, co-location and ownership could become difficult to disentangle, as something may feel as though it is part of your body precisely because it overlaps the real body, which is possible in virtual RHI paradigms. As this is not usually a possible occurrence, the available language to describe something that is in the same space as our body could be that it is part of our body.

Slater (2004) argues that when asking participants about presence after an experience in the virtual environment, they could be similarly retroactively attributing feelings that weren’t there at the time of the experiment. This was an argument we made against long-form questionnaires that took participants out of the virtual environment to rate their experience. We therefore produced a short questionnaire that can be completed quickly while in the virtual environment (van Dam and

Stephens, 2018) and also used this during the mouse cursor experiments. The results from the on-screen scales have been shown to strongly correlate with results from long form, multi-item questionnaires (van Dam & Stephens, 2018). We believe that filling these in quickly while in the virtual environment would help reduce retroactive judgements. We also included reverse coded questions to stop people from clicking through without engaging with the question. However, as they were shorter for the reasons stated above, it meant that we did not include questions that were not relevant to the current task. This means that participants would likely be able to guess the purpose of the experiment and respond how they thought they should.

Explicit judgments can be influenced by pre-existing beliefs and expectations about the task (Moore, Wegner & Haggard, 2009; Gawronski, LeBel, & Peters, 2007). Participants can form beliefs (correctly or incorrectly) about the hypotheses of the experimenter based on cues within the testing situation, these beliefs then influence the responses (demand effects, Corneille & Lush, 2022). Many things can constitute these cues both inside and outside the testing environment, such as the procedure itself and ‘rumours’ about the experiment (Orne, 1962). For example, participants may have told their friends about the experiment after taking part and having the experiment explained to them after their data was collected, and those friends could go on to take part. There may also be cues within the participant information sheet, which needs to contain enough information to obtain informed consent. It is also obvious within the experiment that if there is a change in stimulus, we would be expecting a change in response.

Once they have an idea of the hypotheses, some participants would then want to ‘help’ the experimenter by answering how they think they should. This is especially true if vouchers or credits are being offered as there is an incentive to perform well as a ‘reciprocity norm’ (Corneille & Lush, 2022). This is not to say that the results are consciously faked, the demand characteristics themselves can give rise to subjective feelings through active imagination (Corneille & Lush, 2022) but it is important to consider what results are caused by the intended manipulation and what is coming from another aspect of the paradigm. This is similar to when we have an emotional response to fiction, we know that these are not real events, but we respond as though they are, participants know in the RHI that it is not their hand, but they can imagine how they would react if it were.

Participants may also not be aware that they are producing the demand effects voluntarily, and this can depend on their susceptibility to verbal imaginative suggestion (Corneille & Lush, 2022). Statements such as “I felt as if” or “it seemed as though” which are often used in RHI paradigms promotes imagination (Corneille & Lush, 2022, p.92). For the first trial or set of trials in our experiments, participants may not know how they felt. Once participants had seen the rating statements, which for the VR based experiments would have been in the training phase, they may have used these words to imagine how they should be feeling. Whether there is a difference in feeling between experimental conditions, they could have either guess the appropriate response or applied the words to an altogether different sensation that they were otherwise unable to convey. For example, in the VR target pointing experiment, the size-matched hand was used for the training phase, providing a cue to the participant that we expected them to feel more embodied to that hand.

This imagery provided by the rating statements could also change the internal representations, for example imagining what it would be like if the fake hand was part of the body, giving rise to real effects. The wording of the rating statements could therefore contribute to producing genuine experiences of ownership. Whether this is a problem depends on what conclusions we are aiming to draw. We can argue that our manipulations are driving changes in experience, but not make inferences on the mechanism, as active imagination may be the mechanism when using self-report rating statements. We would still need to attempt to rule out those participants consciously faking their answers, but it would be unreasonable to suggest that all participants would be faking (Corneille & Lush, 2022).

If the experimental setting is providing the imaginative cues, it does bring in to question how much these can be applied outside of this setting. For example, without the training condition with the size-matched hand in chapter 4, we may not be able to claim that size matching is important for ownership when using VR for pain reduction, for example, as it may be that the expectation that this is the hand that you should feel ownership for needs to be set in advance. Corneille and Lush (2022) suggest that clinical interventions using the RHI are simply using the same mechanism as treatments based on imaginative suggestion. As the effect is still there (see for example Coleshill et al., 2017) the treatment is still worth performing, as long as there is justification (in terms of cost and efficacy) for using these in place of other treatments. Having the whole illusory setup may induce a stronger illusion and may be required for some patients to believe that it will work, for example.

Slater (2004) argues that questionnaires aimed at presence cannot confirm its existence without other measures, as the feeling may have been caused by the questions themselves. However, the objective measures that are used may not directly link to the phenomenological feeling that is trying to be measured, and are also not immune to the effects of demand characteristics (Corneille & Lush, 2022). For example, measuring ownership with proprioceptive drift can depend on the wording of the question, as discussed in the introduction (for example see Tsakiris & Haggard, 2005 and Haans et al., 2008). Physiological response is also only useful when the response is obvious, such as the fear response (Slater, 2004) which could also be confounded by surprise. Corneille and Lush (2022) also pointed out that imaginative suggestions themselves can cause a neurophysiological change such as skin conductance (see for example Barber & Coules, 1959).

6.4 Task performance

Looking at task performance across experiments, we found that there was no effect when changing the size of the hand in virtual reality, but there was an effect on task performance when changing the size of the mouse cursor on a computer screen. In both situations, there would have been a size that was more familiar to the participants, the small cursor on the screen and the size matched hand in VR. This could be relating to the translations when converting movements of a mouse on the horizontal plane to the vertical plane, whereas no translation was needed for the virtual hand as the movements were mapped directly.

Enlarging the cursor caused increased completion time and made the path to target less efficient and more curved in order to approach the target from the cursor point. The movement path would need to be calculated for the mouse cursor, which could be hindered by the increase in size and potential for covering the target, as the cursor was visible throughout the trial. The hand was hidden in the movement phase of the VR target pointing task, meaning that increased size would have no effect on the visibility of the target.

However, it should be noted that only the outline of the cursor was opaque, and the fill-colour was transparent, so the majority of the target wouldn't have actually been obscured. Worden and colleagues (1997) also found that viewing information behind transparent cursors did not hinder performance. The increased curvature in path to the target for the large cursor was compounded by non-familiar rotations. This suggests that there was more mental calculation involved for the large cursor, or that the cursor did not behave in the expected way based on its visual characteristics, causing maladaptive changes in pointing behaviour.

To be able to compare the adaptive strategies between the on-screen cursor pointing tasks and the VR pointing task, we would either have to employ open-loop pointing in the cursor experiment so the cursor would be hidden during the pointing phase, or conversely have conditions where the virtual hand is visible in the VR task.

Multi-sensory integration allows both agency and task performance to benefit from sensory feedback from previous attempts (Cesari et al., 2024). Since our aim was to link task behaviour to ratings, future studies should provide visual feedback to promote the sense of agency.

The virtual reaching task was intended to replicate the changes in hand sizes used in Fresnel lens based pointing tasks such as the one used by van Dam and Ferri (2017). An effect of hand size on pointing behaviour was found in their task, even without visual feedback. Open-loop pointing was intentionally used as people are more likely to adapt their behaviour with feedback which would make it more difficult to replicate the same condition.

As we were replicating van Dam and Ferri's (2017) hand size study in a virtual setting, we expected the change in hand size to similarly change reaching behaviour.

Our results suggest that changing the hand size did not change perceived distances, and therefore no adaptation was necessary. This further suggests that the larger and smaller hands were not incorporated, as it has been found that distances are judged relative to hand size but not other familiar objects (Linkenauger et al., 2013). This could be because the hands were not attached to the body, or because eye height did not change with the change in hand size, as discussed in chapter 4.

We could have expected an increase in task performance with the size-matched hand because it was also the most familiar within the environment as it was used for the training phase. The increased ownership did not however increase task performance in the VR pointing task. Fourneret and Jeannerod (1998) found that when participants were unable to see their hand when drawing sagittal lines with a stylus in their task, they were unaware of how much they were moving their hand to compensate for the displayed lines when they were presented at an angle. They suggest that participants were unaware of the sensory signals created by their own movements and that there is “poor conscious monitoring of motor performance” (Fourneret & Jeannerod, 1998, p.1133). This further suggests that the proprioceptive information is not enough on its own to provide participants with useful feedback on task performance.

6.5 Conclusion

In conclusion, the experiments contained within this thesis attempted to provide answers to the following research questions:

Does computer cursor orientation and visual characteristics affect pointing behaviour and the sense of agency in a target pointing task?

We found that the visual characteristics of mouse cursors do affect pointing behaviour. Completion times were fastest with familiar cursor rotations, possibly due to that representation already being part of an internal schema, making it easier to plan movements towards a target. The increased curvature of paths to orthogonal target locations suggests that there is an effect of having to mentally rotate the cursor, as it is easier to plan movements along the axis. Familiar visual characteristics in terms of both the cursor image and rotation promoted the sense of agency.

Expansion of the PPS caused by the familiarity of the tool was also considered as a mechanism for increased task performance, as it has been shown to improve information processing near the tip or effective ends of tools (Gozli & Brown, 2011). This may be more relevant for moving targets where online adjustments to movements need to be made so further experiments with moving targets or that involve a timed reaction would provide more clarity.

Does cursor size affect the feeling of agency and behaviour in a target pointing task?

The larger cursor caused longer completion times for movements that were backwards along the path to the target. The increased curvature of the movement paths in cases where the pointing direction was orthogonal to the cursor orientation was also more pronounced for large cursors. In this case it is likely to be an effect of anticipation that the cursor would obscure the target when planning the movement, even though the cursor was largely transparent. Again, familiar visual characteristics in terms of both the cursor size and rotation promoted the sense of agency. These results show that even in a simple pointing task, cursor appearance and familiarity affect both pointing behaviour and the feeling of agency.

Does familiarity with a tool's size also affect the sense of ownership and agency in a pointing task in a virtual environment?

Familiarity with the size of the virtual representation did increase the ratings of ownership. This however also could have been caused by increased exposure to this hand during the training phase. There was no change in the sense of agency caused by changing the size of the hand, although these rating remained high throughout the experiment.

Familiarity with a tool may be linked to sense of ownership, as there is an internal image of how a tool should look in relation to the body that comes from prolonged use, whereas agency may be more linked to the expansion of PPS and goal directed action, but only when participants are able to monitor or receive feedback on their task performance. While maintaining the open-loop pointing paradigm, so comparisons can be made to magnified and minified hands with Fresnel lenses, feedback could be given to participants through a scoring system, or tactile feedback through controller vibrations if the target is hit, in further experiments. Further experiments would also directly test if perceived distance caused previous changes in behaviour by having conditions where the hand appears closer or further away in the virtual environment.

Does task performance in a virtual tracking task with added delays directly relate to the subjective feelings of ownership and agency?

We found that increasing delay increased spatial and temporal errors, and that task performance in both spatial and temporal terms positively correlated with the feelings of ownership and agency. Agency and the spatial component of task performance had the highest correlation. This suggests that visual feedback of task performance promoted the sense of agency over the movements.

However, we found that ownership was generally rated low even though it continued to diminish with increasing delay. This suggests that increased task performance is likely to be caused by the increased congruency of information, rather than the increase in ownership in immersive VR environments (see for example Odermatt et al., 2021).

Task performance therefore doesn't predict the level of ownership, but having an avatar that doesn't behave as predicted seems to further decrease ownership. When considering goal-directed movements, we should be aware that manipulations aimed at reducing the senses of ownership could make tasks inherently harder, as they would reduce the familiarity with the way the body part looks or moves, which would require more mental translation to integrate into existing schemas.

Our experiments also support the consensus that the visual similarity of the tool to the real hand is also important for this sense of ownership even in active movement conditions.

Do manipulations that affect the sense of ownership, such as asynchronous movement conditions, also cause baseline skin conductance to increase?

This experiment in chapter 5 demonstrated that conditions with extreme delays intended to manipulate the level of ownership and agency can also cause an increase in skin conductance in the subsequent trials. Delays of up to 600ms did not have this effect and so are unlikely to affect the ability to detect a threat response.

In conclusion, visual appearance of the tool does have an effect on the subjective feeling of ownership, but feedback on task performance is necessary for the sense of agency in virtual tasks. This work on agency and familiarity in virtual tasks and with virtual tools can help with the optimisation of user interfaces for education and training, and help developers make informed decisions on what cursor might be optimal, but also balance whether the change creates enough benefit in terms of tasks performance to risk reducing people’s familiarity with the tool.

Considering the effect of delay on the feeling of agency and task performance can give us a better understanding of how professionals can cope in teleoperator settings where, depending on the system, delays might be inherent to the setup. The role of agency is important when considering very complex remote tasks such as robotic surgery (for a review see Cesari et al., 2024).

The study of body ownership combined with Virtual Reality (VR) is also relevant to various avenues of research as well as having many real-world applications. VR is currently being investigated as a tool for rehabilitation (Holden, 2005; Viñas Diz et al., 2016), treatment of pain (Shahrbanian et al., 2012) and even adjustment of social attitudes to gender or race (see Maister et al., 2015). VR has also been explored for various training paradigms such as health and safety and training with specific equipment and tasks in construction and engineering (Wang et al., 2018), as well as for training in emergency situations (Xie et al., 2021). This work on ownership illusions in VR has the potential to find a further application in optimising the treatment of body dysmorphic conditions, through ownership of differently shaped full-body avatars. Understanding the sense of ownership is important for self-other distinction, which has implications for cognitive schizophrenia. For these treatments to work a sense of ownership of the virtual avatars is required. This work will therefore be informative about the conditions that optimise this sense of ownership in VR and therefore optimise these treatments.

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Appendix A: Statistical power considerations

In order to evaluate statistical power, the mean and covariance of the results for each experiment were calculated, and used to simulate 1000 reruns of the experiment, as a function of the sample size. For each effect, we noted the proportion of simulations on which a significant effect was observed, with an alpha value of 0.05. To assess the sensitivity of this approach to variation in the size of the effect, this was repeated with mean differences between conditions reduced by a factor of 0.5, or increased by a factor of two.

Chapter two: The effect of cursor image and orientation on pointing behaviour

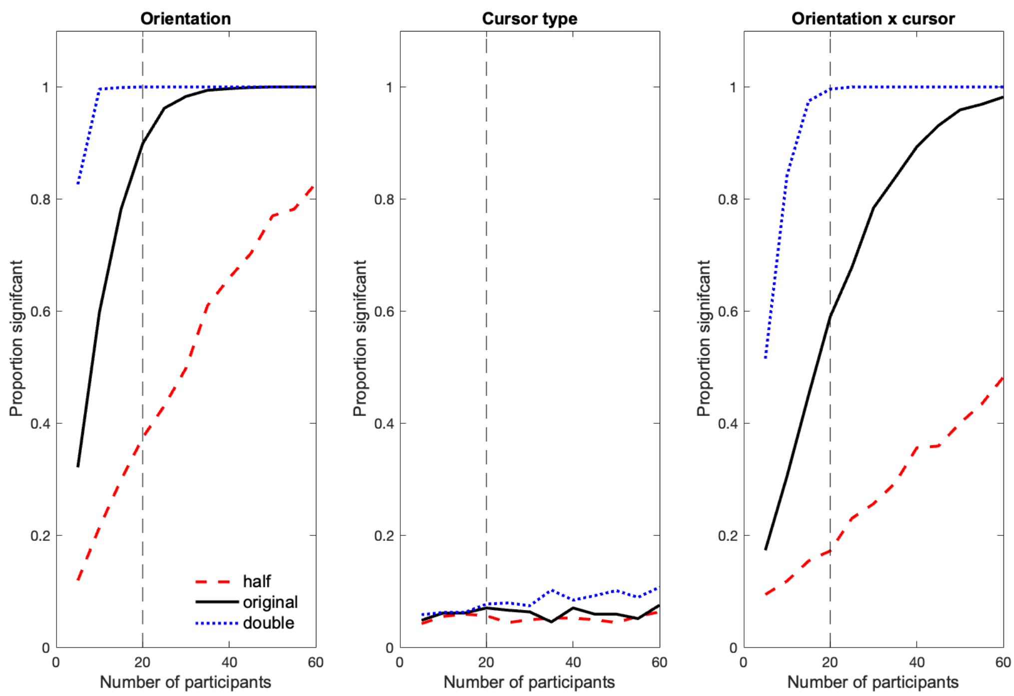

Figure 1: Simulated effect of sample size on statistical power showing the proportion of significant results for completion times as a function of sample size for (left-to-right) orientation, cursor type and their interaction. Black lines are based on the size of effect found in the actual experiment, red dashed and blue dotted lines show results with half and double the differences between means, respectively.

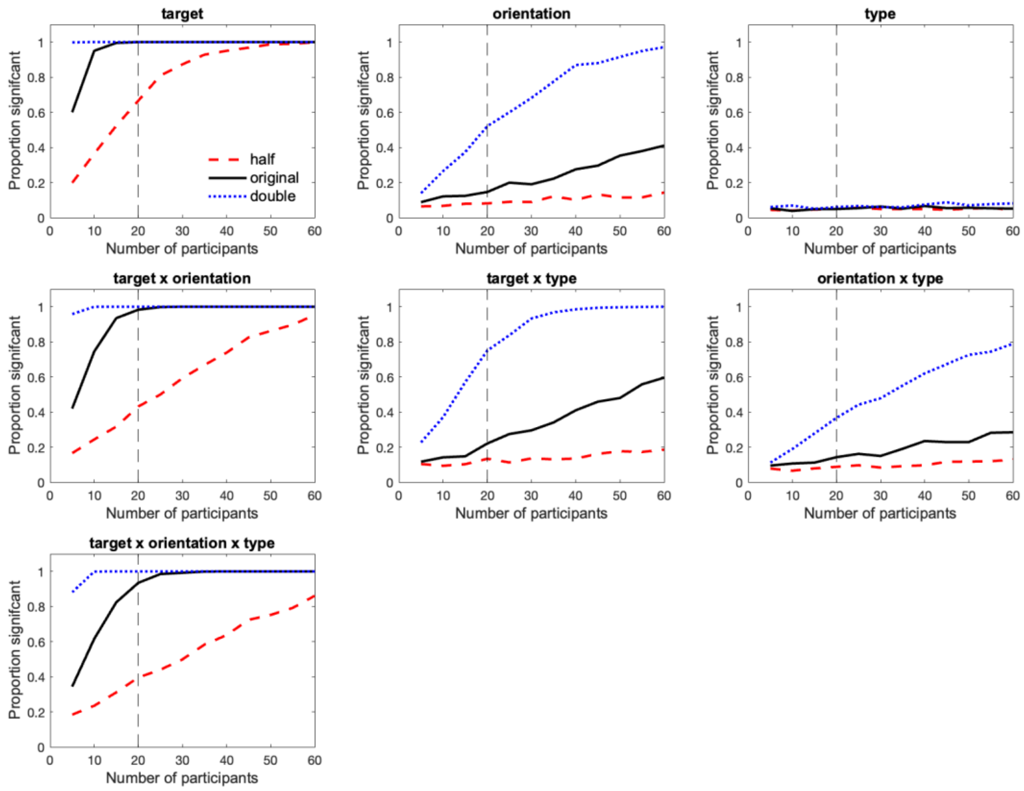

Figure 2: Simulated effect of sample size on statistical power showing the proportion of significant results for deviations from straight ahead as a function of sample size for target location, orientation, cursor type and interactions. Black lines are based on the size of effect found in the actual experiment, red dashed and blue dotted lines show results with half and double the differences between means, respectively.

Chapter three: The effect of cursor image and orientation on pointing behaviour

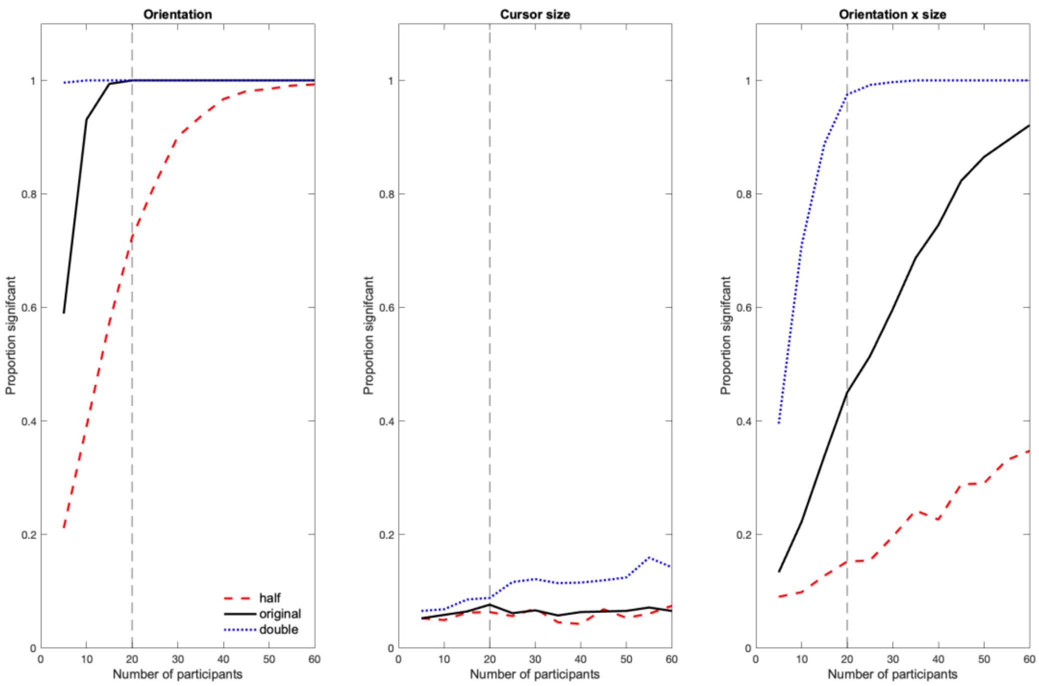

Figure 3: Simulated effect of sample size on statistical power showing the proportion of significant results as a function of sample size for (left-to-right) orientation, cursor size and their interaction. Black lines are based on the size of effect found in the actual experiment, red dashed and blue dotted lines show results with half and double the differences between means, respectively.

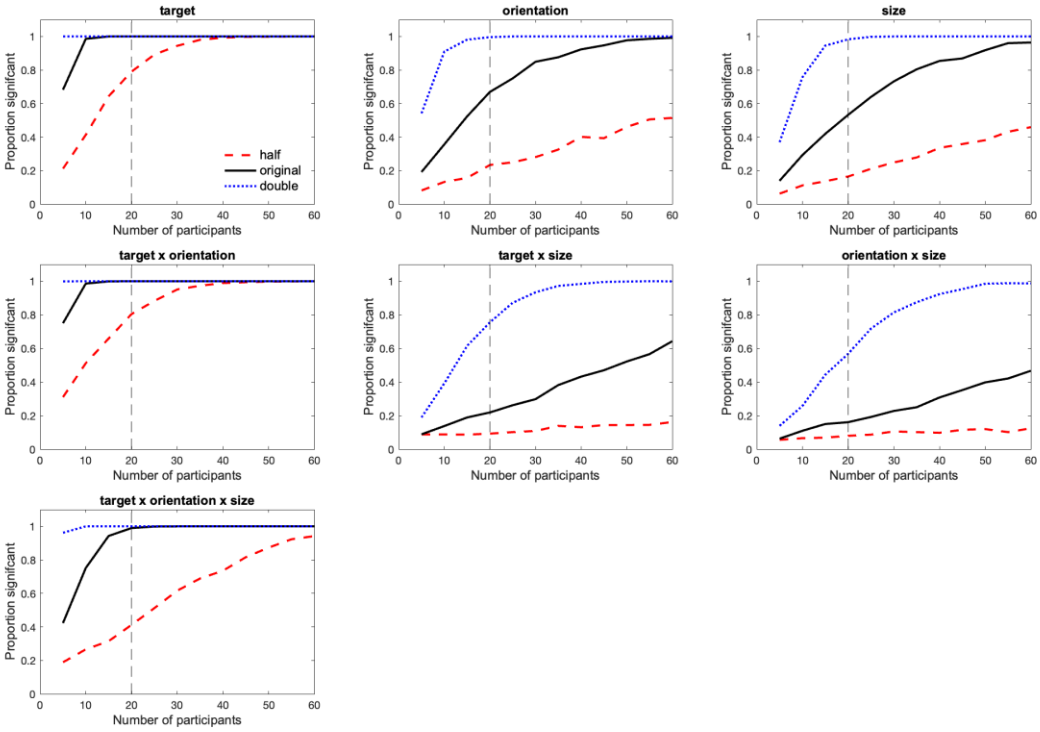

Figure 4: Simulated effect of sample size on statistical power showing the proportion of significant results for deviations from straight ahead as a function of sample size for target location, orientation, cursor size and interactions. Black lines are based on the size of effect found in the actual experiment, red dashed and blue dotted lines show results with half and double the differences between means, respectively.

Chapter four: The effect of virtual hand size on pointing behaviour and the sense of ownership and agency

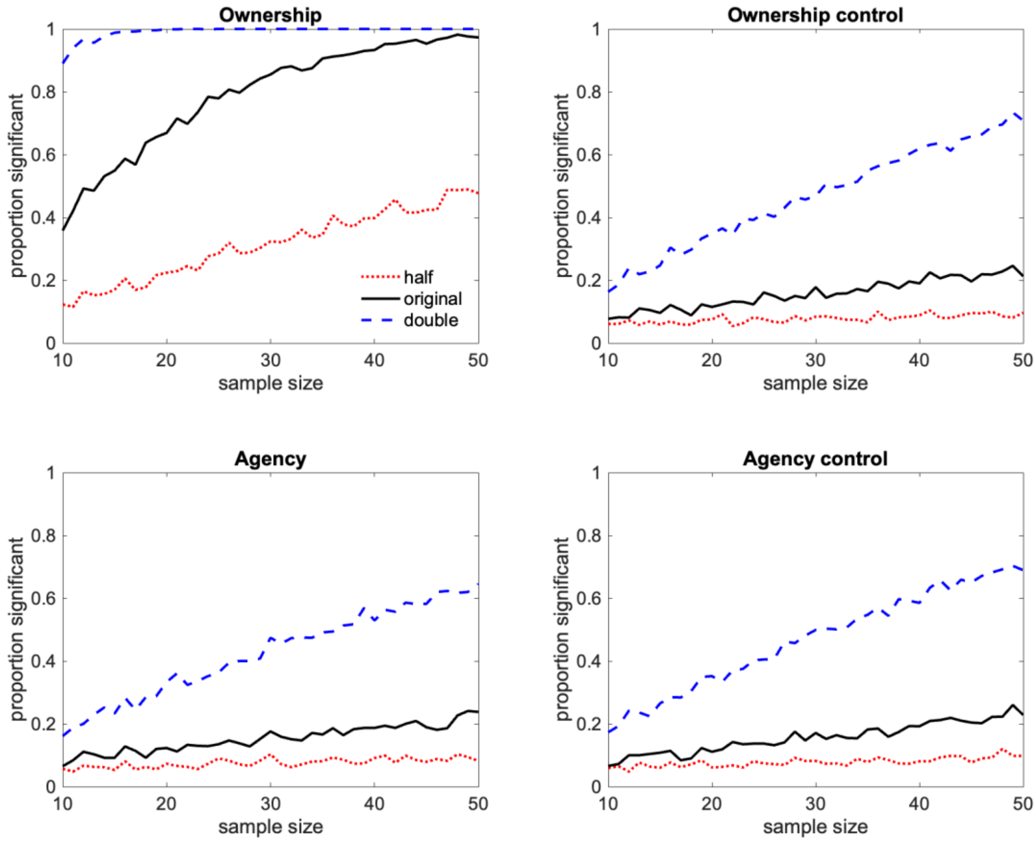

Figure 5: Simulated effect of sample size on statistical power showing the proportion of significant results as a function of sample size for the four ratings. Black lines are based on the size of effect found in the actual experiment, red dashed and blue dotted lines show results with half and double the differences between means, respectively.

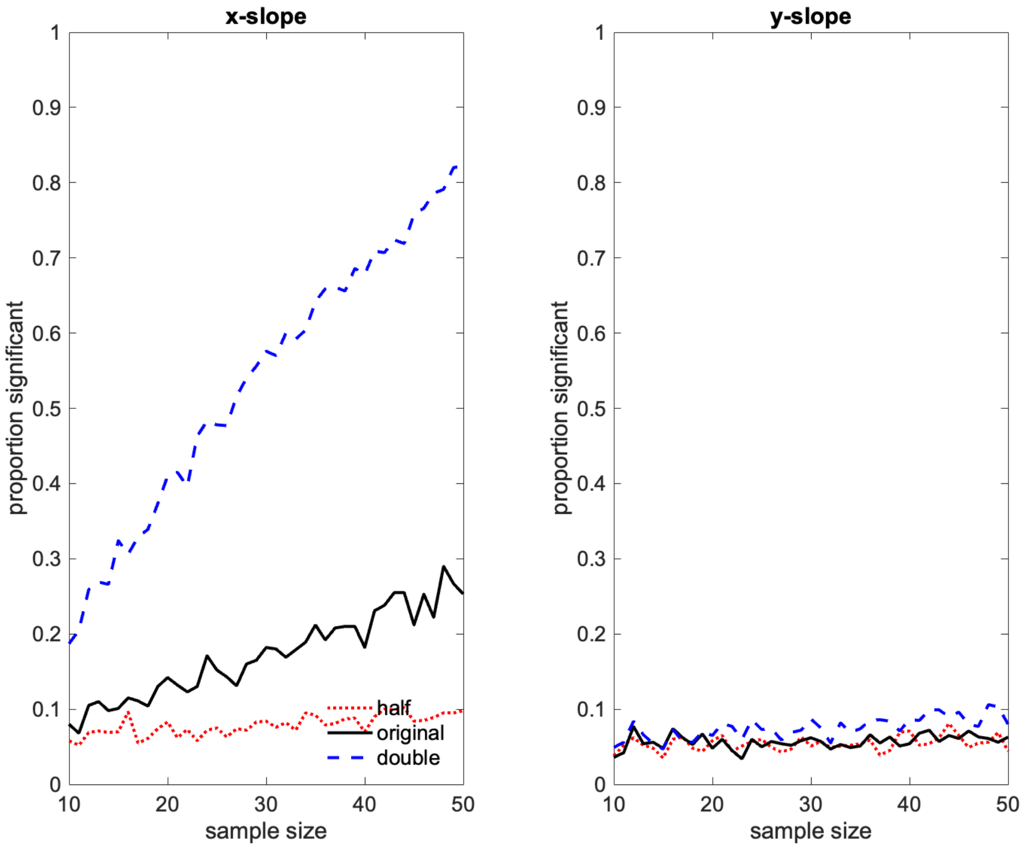

Figure 6: Simulated effect of sample size on statistical power showing the proportion of significant results as a function of sample size for the slope errors. Black lines are based on the size of effect found in the actual experiment, red dashed and blue dotted lines show results with half and double the differences between means, respectively.

Chapter five: The effect of delays in a virtual tracking task on the feeling of ownership and agency

There were large effects in this experiment, so calculations of power as a function of sample size for assumed true effects of the size reported are not insightful. Rather, effect-sizes are reported here. For spatial and temporal errors, effect sizes were calculated as Fisher's f values of 3.8 and 6.23, respectively. Post-hoc power analysis provided an estimated of achieved power of >0.99 for both measures. For ratings, effect sizes are reported as Kendall's W, for which a large effect is considered to be one with a value of greater than 0.5. The values obtained are 0.913 for agency, 0.906 for agency (control), 0.570 for ownership, and 0.202 for ownership (control). Thus, only the ownership control response did not produce a large effect size.