Investigating the effects of mid-air haptics on the sense of agency

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Acknowledgements

What they don't tell you about doing a PhD, is just how much life can happen during such a long project. Among the many things, was losing many important figures along the way, whether during that treacherous pandemic or otherwise. So, to dedicate this to my Grandma, who was an absolute powerhouse and truly loving person, and her hilarious yet steady rock, Grandad. The other hub of the family, my Auntie, who knew everyone and everything. My Godmother, who could make anyone feel at home. All are dearly missed. To keep life up amidst the downs then, were important figures I am incredibly thankful for.

First and foremost, my supervisor, Dr James Moore. I could not have asked for a better person as a mentor, someone who struck the ideal balance between giving me independence and guidance when need be. I'm always stunned when he is somehow able to see the logic within my scatterbrain and ground the airy ideas in the real world. Calm yet clearly passionate, he is not afraid to be persuaded by sound argument nor point out a flawed one; I have thoroughly enjoyed our many critical discussions over the years. Thank you.

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Last but certainly not least, I want to thank me. Just kidding (Snoop Dogg made me do it); rather, my friends who this simply would not have been possible without. No, really. They have been there through the absolute thickest of it, when I couldn't seem to see through the clouds. Those who got me there, and the fellow PhD students who managed to put up with my chaos in the office along the way, I hope they know just how grateful I am.

Abstract

The sense of agency (SoA), the feeling of exerting causal influence over the environment via our own actions, extends to human-computer interaction (HCI). Recent advances in mid-air haptic technology were developed to accompany contactless hand-tracking interactions with touch sensation. An interdisciplinary principle underpins this thesis investigating effects of mid-air haptics on SoA. That is, I seek to make use of this manipulable haptic feedback for novel insights into the psychology of agency, and also hope that this research (using robust psychological methods) provides novel insights into user experience when using the technology.

In Chapter 2, the agent is situated in the virtual world where mid-air haptics are integrated. The first experiment showed the salient presence (versus absence) of mid-air haptics can increase explicit SoA. The second experiment revealed that subtly different haptic types can modulate implicit SoA. These signify differences noted in the feeling and judgement of agency and have implications for integrating mid-air haptics in virtual reality.

Chapter 3 situates the agent in the automotive context, where mid-air haptics is used in gesture-based interactions. The first experiment showed that haptic feedback strengthened SoA compared to visual feedback. A second experiment looked at mid-air haptics in a driving simulator scenario and showed that mid-air haptics increases SoA over in-vehicle infotainment compared to typically used audio feedback. These findings suggest mid-air haptics is particularly beneficial for gesture-based interactions.

A more fundamental yet distinct aspect of SoA was turned to in Chapter 4; namely the awareness of intention. Here we manipulated the predictability of receiving mid-air haptic feedback. In a first experiment we found a delayed awareness of intention under uncertainty. In a second experiment we found that this delay was as a function of the probability of haptic

feedback. This supports an anticipatory mechanism for formulating intentions and may have implications for certain volitional disorders, such as schizophrenia.

In the concluding chapter, the findings are summarised and implications for psychology as well as practical HCI applications are discussed.

Disclaimer: some of the research in this thesis has been presented at conferences and/or published.

Chapter 2, Experiment 1: Evangelou, G., Georgiou, O., & Moore, J. (2023). Using virtual objects with hand-tracking: the effects of visual congruence and mid-air haptics on sense of agency. *IEEE Transactions on Haptics*, *16*(4), 580-585. https://doi.org/10.1109/TOH.2023.3274304

Chapter 2, Experiment 2: Evangelou, G., Georgiou, O., & Moore, J. (2024). Mid-air haptic congruence with virtual objects modulates the implicit sense of agency. In *Haptics: Science, Technology, Applications: 14th International Conference on Human Haptic Sensing and Touch Enabled Computer Applications, EuroHaptics 2024, Lille, France, June 30- July 3, 2024, Proceedings*. Springer Nature. https://link.springer.com/conference/eurohaptics

Chapter 3, Experiment 1: Evangelou, G., Georgiou, O., Brown, E., & Moore, J. W. (2025). Sense of agency in gesture-based interactions: modulated by sensory modality but not feedback meaning. *Frontiers in Computer Science*, *7*, 1511928.

Chapter 3, Experiment 2: Evangelou, G., Georgiou, O., Brown, E., Hine, N., & Moore, J. (2024, September). Mid-Air Haptic Feedback Improves Implicit Agency and Trust in Gesture-Based Automotive Infotainment Systems: a Driving Simulator Study. In *Proceedings of the 16th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 116-124). https://doi.org/10.1145/3640792.3676882

Chapter 4, Experiment 1: Presented at *26th annual meeting of the Association for the Scientific Study of Consciousness,* New York University, 22nd-25th June 2023)

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Chapter 1

General introduction

Many actions we initiate are with the intention to bring about a change in the existing state of the environment. To cross the road safely, we press a stop button and wait for the light to turn red. To avoid an accident, we press the breaks on a car to stop. The underlying psychological process here is a complex series of events: an intention (safety), an action (press) and self-attributing its effect (red light/motionless car). Together however, it feels like one seemingly fluid experience. This unified process and accompanying experience constitutes the sense of agency. That is, the sense that we are in charge of our actions and have the capacity to influence the outside world.

In an era of rapid technological advancement, an increasing number of our interactions now involve computers. Traditionally these interactions have still required physical touch, whether clicking to go onto the next page or touching the screen to manipulate a map. However, recent advances in technology now enable touchless mid-air interaction that removes the need for mediated physical contact with a device.

Although touchless systems offer great promise in the realm of human-computer-interaction, they also pose challenges, especially for the sense of agency. Sensory feedback, including tactile (haptic) feedback is considered to be crucial for establishing and representing the self in action (de Vignemont & Haggard, 2008; Moore & Fletcher, 2012). Losing this feedback, as is the case with touchless systems, threatens to undermine user's sense of agency. In recognition of this, mid-air haptic technology has been developed to provide tactile stimulation directly to the hand in a touchless mid-air interaction, thus restoring the sensation of touch.

Mid-air haptics is an important development, but the effect of this on user experience, in particular the experience of agency, has not been systematically investigated. In this thesis I will address this, by investigating the role of mid-air haptics in modulating the sense of agency with human-computer interaction. I will present a series of experiments with different types of interactions that correspond to the different facets of agency. This work will not only provide insights into the psychology of user experience but, using these technologies, we will also gain insights into the fundamental role of haptics in sense of agency. In the remainder of this chapter I will introduce the concepts and review the relevant literature which builds the rationale for the empirical work presented in the thesis.

1.1 The sense of agency

The experience of initiating action to exert influence over the external world is referred to as the sense of agency (SoA) (Moore, 2016). While agency itself is a broad term, bearing on wider concepts of freedom in Sociology (Emirbayer & Mische, 1998) and decision-making among corporations (Mulgan, 2019), the psychological perspective focuses on the more intimate connection to our motor system. Gallagher (2000) uses the case of involuntary movement to distinguish it from the sense of ownership (SoO) – with involuntary movements there is a SoO but no SoA, whereas with voluntary actions there is both. This shows that SoA is additional to basic somatic experience.

1.1.1 Methodology and measurement

Intentional actions and associated outcomes are the key components of agency. A typical experimental paradigm involves the manipulation of an action and/or its outcome. So-called explicit measures will record participants' judgements of agency. These may be categorical self-other judgements, where the participant's job is to make an agency attribution (Farrer &

Frith, 2002; Waltemate et al., 2016). Otherwise, a rating scale may be used to report the amount of control they felt over their actions and effects (Haering & Kiesel, 2015; Sidarus & Haggard, 2016).

Methods that capture SoA implicitly have also been developed, removing issues associated with explicit measures (such as demand effects). One such measure is sensory attenuation, which refers to the attenuation of the perceived intensity of (sensory) stimuli caused by a self -rather than other-generated action. This has been demonstrated by lower reported ratings of auditory tone intensity (Sato, 2008), attenuated somatosensory signals in response to tactile stimuli (Blakemore et al., 1998), and discrimination sensitivity to visual stimuli (Roussel et al., 2014).

A more widely used implicit SoA measure is intentional binding, referring to the perceived compression of time between voluntary actions and their effects (Moore & Obhi, 2012; see Figure 1.1). This stems from an experiment by Haggard et al. (2002) investigating the difference in the subjective experience of time for voluntary and involuntary actions and their subsequent effects. In this experiment when participants voluntarily pressed a button that caused an auditory tone (operant), button-presses were experienced later in time and tones earlier, compared to when each was performed or heard independently (baseline). Furthermore, for involuntary movements (induced by transcranial magnetic stimulation applied over the motor cortex, causing a movement of the index finger), the opposite effect was found such that button-presses were experienced earlier and the tone later. Therefore, this temporal compression perceived for self-generated, voluntary actions and subsequent effects appropriately captures SoA in an implicit fashion. The paradigm has been utilised to examine various aspects of SoA, including cognitive (Howard et al., 2016), affective (Christensen et al., 2019), social (Stephenson et al., 2018), clinical (Voss et al., 2010), and neural correlates (Moore et al., 2010).

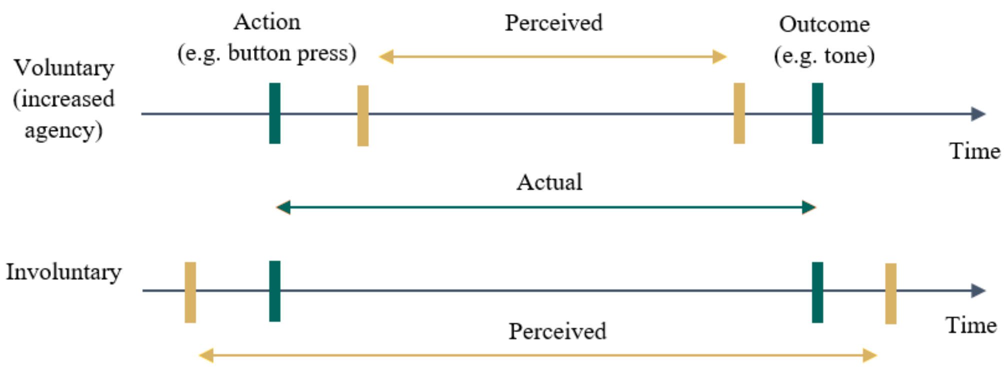

Figure 1.1. *Intentional binding as illustrated by the perceived compression of time between voluntary actions and their outcomes, associated with an increased sense of agency*

The relationship between implicit and explicit measures is somewhat inconsistent, leading to questions of whether they measure the same process (Dewey & Knoblich, 2014). One suggestion is a phenomenological distinction at the level of awareness, between *feeling* and *judgement* of SoA (Synofzik et al., 2008). The former being implicit in the motor act and the latter for explicit attribution. This is corroborated by findings of a hierarchical order, whereby motor control poses less influence when goal-directed behaviour succeeds (Kumar & Srinivasan, 2014), and these differential effects reflected in implicit and explicit measures (Kumar & Srinivasan, 2013). Therefore, SoA may operate differently at higher -and lower-level orders of cognition. In addition, given the multiple processes that derive SoA (intention, action and effect), manipulations may not affect all aspects of this experience and each one measure may not capture all the underlying mechanisms.

1.1.2 Theoretical accounts of agency

Historically, there have been two influential theoretical accounts of SoA that oppose one another in terms of the origins of the process. Wegner and Wheatley's (1999) 'theory of apparent mental causation' states the key influence of situational cues in determining the attribution of agency. In this way, SoA is a post-hoc rationalisation depending on whether it is plausible that a given change in the environment could have been caused by the self. That is, causality becomes apparent after the fact.

The opposing theory, termed the 'comparator model' (Blakemore et al., 2002; Frith et al., 2000), places emphasis on the motor system internal to the individual. Here, SoA arises from efferent signals generated by the motor system which feed forward the relationship between actions and outcomes. In this way, SoA operates largely from the internal model of the individual which is used to compare to closely related signals. That is, causality is determined largely through internal motor predictions.

More recent accounts attempt to reconcile these views, suggesting that internal motor signals *and* contextual cues influence SoA (Synofzik et al., 2013). Moore et al (2012) propose an 'optimal cue integration approach', according to which the influence of internal motor signals and contextual cues is dependent on their reliability. Here, when motor control signals are not a reliable source for the agent, they must place weight on the importance of situational cues, and vice versa. That is, causality is determined by the most reliable source of information. In the following parts of this section, I further define the concepts and discuss the evidence on which they're based.

The theory of apparent mental causation

The core tenet of the theory of apparent mental causation is that the conscious experience of willing an action is retrospective and therefore subject to illusion (Wegner, 2004). Wegner and Wheatley (1999) state that separate unconscious processes underly thought and action but can be experienced as causally related (Figure 1.2). We interpret an event as caused by the self should three principles be met: priority, consistency and exclusivity. The event should follow the thought prompt, this gives priority to the self. There should also be consistency between the action and the thought. Finally, other plausible causes for the event should be less salient so the source of the action remains exclusive to the self. When these conditions are met, it becomes *apparent* that we were the agent, even for events we may not have been.

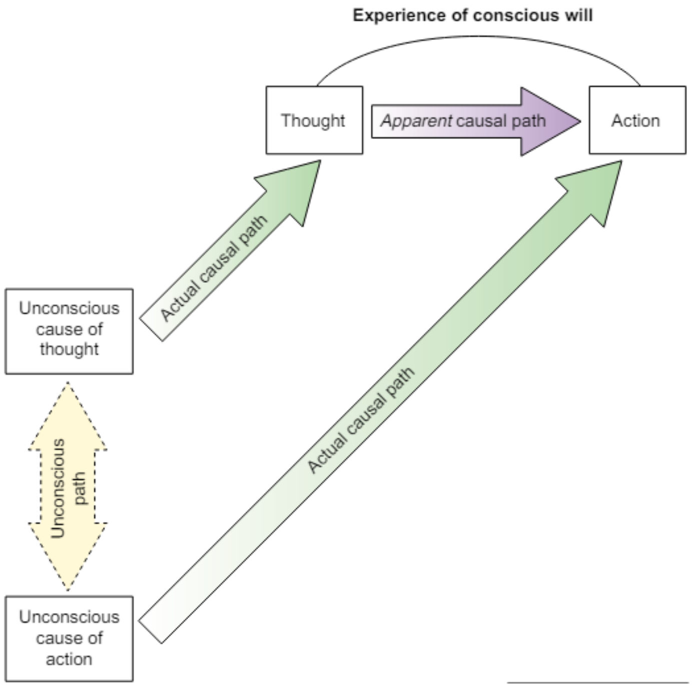

Figure 1.2. *Apparent mental causation model (Wenger, 2003).*

Wegner and Wheatley (1999) conducted an experiment to test this theory, whether SoA can be induced for an event that was actually caused by someone else. Both the participant and a confederate place their hands on a mouse that controls a cursor and are asked to move it around the screen displaying multiple objects. At different times, they would be required to stop the cursor and rate how much they intended to make the stop happen or if they simply allowed it to happen. While moving the cursor, participants listen to music and words to which they're led to believe is merely a mild distraction. For forced stop conditions, words served as a prime for a specific object on the screen, played either 30sec, 5sec or 1sec before/after the confederate would stop on the corresponding object. They find that when primes occurred in the 1-5sec window, rated intention to stop was not only higher, but also comparable to rated intention in the unforced stop conditions. It is important to note that primes did not affect stopping behaviour in the unforced conditions, indicating they did not contribute to the stopping in the forced conditions. By manipulating the priority, consistency and exclusivity principles then, participants arrived at the mistaken belief that they had caused an event.

To further support this theory, the manipulation of the aforementioned principles has been explored with vicarious movement. In Wegner, Sparrow and Winerman's (2004) experiment the participant was stood in front of a mirror wearing a cloak, meaning they could not see their own arms. An experimenter was stood behind the participant, blocked from view by a screen. The experimenter placed their arms in a position that was similar to where the participants would be. Both wore headphones, over which was played gesture words that may or may not correspond to hand movements subsequently made by the experimenter. For example, the participant may hear the word "OK" and see the experimenter making the OK gesture with their hands. Participants were asked to rate the amount of control they felt they had over the movement of the hands (which belonged to the experimenter). Wegner et al found that ratings of control were significantly increased when the gesture preview matched the subsequently performed gesture. This shows that simply having a preview of what is about to happen before it does, is sufficient to generate a sense of agency. This is consistent with the principles of the theory of apparent mental causation.

The comparator model

As noted previously, the so-called comparator model (Figure 1.3) offers an alternative theory of sense of agency. This model proposes that awareness of action *is* tied to the process of action, building upon fundamental models of motor control itself (Wolpert, 1997). According to this model, before we move, we start off with a goal or intention. On the basis of this we generate a representation of the desired state of the motor system, which allows us to specify a motor command. This motor command gets sent to the muscles, which move, and these movements generate sensory feedback. Using this feedback, we can estimate the actual state of the system.

We can then compare the estimated feedback with the desired feedback. Any discrepancy is relayed to the controllers which send out new motor commands, until our actions are successful.

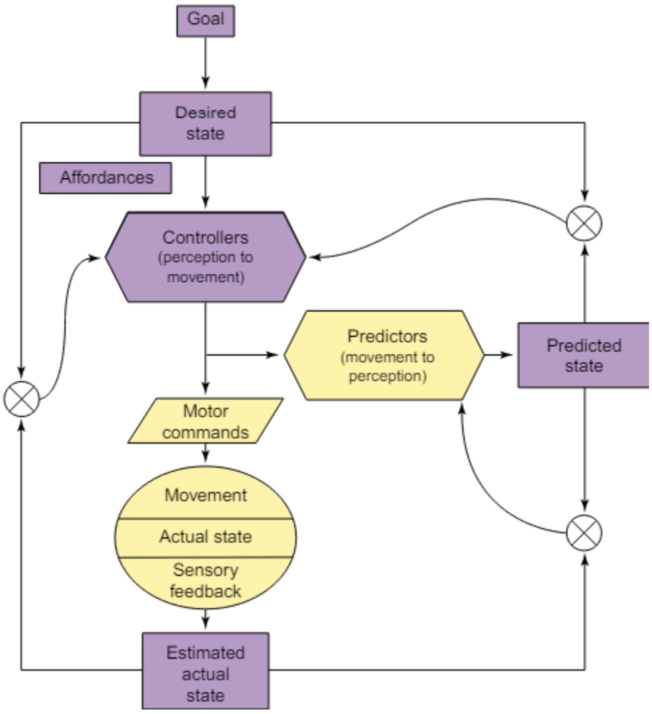

Figure 1.3. *Comparator model (Blakemore. Wolpert & Frith, 2002).*

However, a motor system operating purely on the basis of this simple feedback loop would be inefficient and prone to failure (i.e. the organism would not last very long as errors would be apparent only after the organism has committed them). To solve this problem, the system also contains predictors, which receive copies of the motor commands that are being issued. These are used to predict the likely state of the system i.e. what the sensory consequences of movement will be. These predictions are important because they allow the motor system to correct itself in advance, so that we can correct any mistakes online before we have made them. Moreover, it has been proposed by Frith and others (e.g. Frith et al., 2000; Frith et al., 2000; Sarah-jayne Blakemore & Frith, 2003) that these predictions are important for generating our SoA. The basic idea is that the SoA is based on our ability to predict the sensory consequences of movement. We compare predicted and actual sensory feedback; if there is a match then the system produces a SoA, if a mismatch then there is no SoA.

There is empirical evidence in support of the comparator model, showing a crucial role of internal motor signals in the perception of action consequences. One prediction from the comparator model is that the perception of predicted sensory feedback will be attenuated; that which is predicted is subtracted from the final sensory percept, with the agent only aware of the error signal (it is this computation which informs sense of agency). This prediction has been confirmed across multiple studies. For example, Blakemore et al. (1998) found that tactile stimulation produced by the self is perceived as less ticklish than when externally produced. Neural responses to the tactile stimulation were also looked at using functional magnetic resonance imaging (fMRI). These revealed increased activation in the somatosensory cortex for externally produced sensations.

A study by Voss et al. (2006) further established the role of efferent motor commands in attenuating self-generated sensory signals. Using transcranial magnetic stimulation (TMS) over the primary motor cortex during a self-generated movement, they delayed the movement onset without affecting the movement itself. Tactile stimulation during this delay period (pre-movement) was attenuated comparably to a typical movement condition. This highlights the importance of predictive premotor signals in the sensory attenuation effect (attenuation could occur before movement onset). Given that attenuation is thought to be a marker of sense of agency, this experiment also confirms the role of prediction in that experience.

Additional support for the comparator model comes from disorders in which there are abnormalities in the awareness of action (Blakemore et al., 2002; Frith et al., 2000). For example, certain individuals with schizophrenia suffer from delusions of control (or passivity). These individuals typically feel as though someone or something else is controlling their movements. It has been suggested this is the result of predictive impairments in the motor control system (Voss et al., 2010). This is confirmed by findings showing that patients with delusions of control can tickle themselves (Blakemore et al., 2000). Three groups of participants were tested for their perception of self-produced versus externally produced tactile (tickle) sensations: patients (schizophrenia or affective disorders) with and without hallucinations/passivity experiences, and control subjects. Difference scores were taken to indicate whether the intensity/tickly sensation was rated lower (attenuated) in the self-produced condition. Sensory attenuation was experienced in the control and symptoms absent groups but not in the symptoms present group. This suggests the suppression of self-produced sensory signals, driven by the forward motor prediction, is impaired specifically in patients with an aberrant experience of agency. This finding has also been replicated in non-clinical individuals who display self-reported passivity symptoms (Lemaitre et al., 2016; Whitford et al., 2017).

Together, evidence of a crucial role for internal motor signals challenges the key assumption of Wegner and Wheatley that the experience of initiating an action is ultimately a situational illusion. Notably, the empirical evidence to which these two theories are based on differ critically in their experimental paradigms. Wegner and Wheatley's (1999) study purposefully introduce ambiguity via a confederate whereas Blakemore et al (1998) were explicit with the participant as to whom the action was generated by. With the former lending potential to situational cues and the latter providing clearer internal cues, this may underly the findings they base their distinctly different conclusions on. It follows that both cues may be important depending precisely on the circumstances under which the agent operates in. The cue integration approach thus takes this into consideration.

The cue integration approach

A Bayesian framework forms the core of the cue integration approach, essentially that one must appropriately determine the probability they are the agent based on the *reliability* of available *cues* (Moore & Fletcher, 2012; Moore et al., 2009; Synofzik et al., 2009). Moore and Fletcher (2012) note the inherent uncertainty in both internal motoric cues and external situational cues. The former due to the probabilistic nature of the sensorimotor system and the latter due to noise in the perception of the environment. To deal with this, a cue integration view posits that cues are weighted relative to their reliability. For example, should sensorimotor information become absent or unreliable, one would rely more on environmental cues. Should a voluntary action and its motoric cues be reliable to an individual, post-hoc contextual information may not change the agent's mind.

This cue integration approach is corroborated by empirical research. For example, using a factorial design, Moore at al. (2009) compared levels of movement type and prime congruence on SoA in a button press-tone binding paradigm. The button was pressed either voluntarily by the participant or involuntarily induced by the experimenter. High and low pitch tones were primed either congruently or incongruently prior to the action made. A significant interaction showed that binding was more strongly modulated by the primes when the movement was made involuntarily. This suggests these contextual cues exert more influence in the absence of reliable motoric cues. Following up on this, their second experiment examined the effect of temporal contiguity by presenting these primes either 1sec or 10sec before an involuntary action. A significant interaction here showed that not only did the 1s primes strongly modulate binding, the 10s primes had no effect at all. This speaks more directly to the two aforementioned theories by demonstrating Wegner and Wheatley's (1999) priority principle is indeed valid particularly when Frith et al.'s (2000) predicted state representation is compromised.

Experiments manipulating outcome probability also show that the reliability of internal and external cues determines their influence on sense of agency. In an experiment by Moore and Haggard (2008), participants made voluntary button-press actions that caused a tone to occur either 50% of the time or 75% of the time. When outcome probability was high (75%), there was a shift in the perceived time of the action towards the outcome, even on trials when it did not occur. When outcome probability was low (50%), this shift in the perceived time of the action only occurred on trials that caused a tone. This suggests that SoA uses predictions when they are reliable but relies on external sensory feedback when they are not.

1.2 Agency in human-computer interaction

As our actions and their effects extend beyond the physical world when using technology, so too does the capacity to experience agency. In the field of human-computer interaction (HCI), there has long been a focus on fostering control over a system when one is designing a user-interface (Schneiderman & Plaisant, 2004). This reveals the fundamental importance of SoA to HCI. In recognition of this, there has been an increase in research applying methods from cognitive neuroscience to measure SoA in various areas of HCI, for example, with computer assistance dynamics (Coyle et al., 2012) and human-robot cooperation (Barlas, 2019). In the following parts of this section, I will outline a core conceptual challenge for agency in HCI, and the move toward an interdisciplinary approach.

1.2.1 The gulf of execution and evaluation

A key challenge for HCI is to effectively bridge the gap between the intention of the human and the state of the computer. This involves optimally translating the user's intention into a system change, and in turn relaying the current system state to the user; the former referred to as the *Gulf of Execution* and the latter the *Gulf of Evaluation* (Figure 1.4) (Limerick et al., 2014; Norman, 1986; Williamson et al., 2009). Thus, these intentional actions and perceived outcomes illustrate a direct transfer of SoA to HCI.

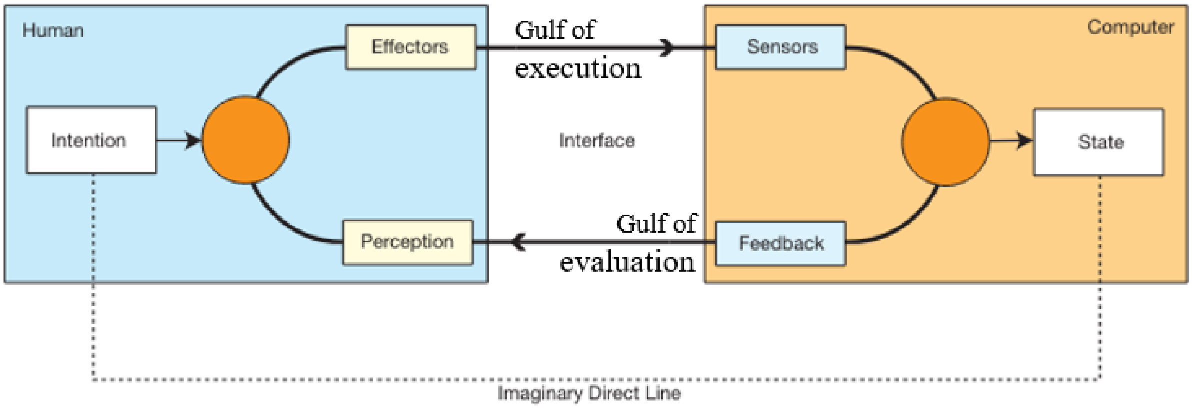

Figure 1.4. *Gulf of execution and gulf of evaluation model adapted from Norman (1986), Williamson (2009) and Limerick et al. (2014).*

The way in which a user executes an action to bring about their intended change to the system is largely determined by the mode of input (Norman, 1986). Different devices require varying motor commands and action selection which can affect SoA. For example, research has shown that SoA diminishes with speech input (Limerick et al., 2015). When participants used a voice command to make the change to the system, this resulted in a loss of SoA as compared to a traditional keyboard button. Additionally, research has found an increase in SoA for skin input (Bergstrom-Lehtovirta et al., 2018; Coyle et al., 2012). When participants used a device that allows them to press on their own skin to influence a system, this strengthened their SoA as compared to a traditional keyboard or touchpad. Together, this demonstrates the effect of input modality on SoA, revealing the potential importance of bodily input.

To evaluate the success of the action, the user must interpret the new state of the system and so the feedback given is crucial (Norman, 1986). This relationship is arguably more complex due to the variety of ways this feedback can inform the agent. An obvious factor here is the feedback given for carrying out the action itself. For example, research has shown that latency between the user's movement and the on-screen representation of the movement negatively impacts SoA (Berberian et al., 2013; Evangelou et al., 2021). A more complex factor is to achieve an appropriate relationship with the user's intentions. This is typical with assistive feedback, where research has examined how a computer assisting the user to attain their goal affects SoA. In a study by (Coyle et al., 2012), participants were required to move a cursor to the goal destination and assistance of this was manipulated at 4 levels: no assistance, mild, moderate, and high. Mild assistance both helped achieve the goal and maintained SoA, which appeared to drop off at the moderate assistance level. This suggests a threshold at which the computer can intervene before the agent may feel a loss of responsibility for the outcome. Finally, feedback for the outcome of the action can retrospectively inform the agent. One example here is that latency between a user's action and the effect it causes is potentially more impactful than the movement-related latency (Evangelou et al., 2021; Winkler et al., 2020). Additionally, research has revealed congruency of an effect such as arrow (mis)direction (Barlas & Kopp, 2018) and even arousal via the colour of a visual effect (Wen et al., 2015) can affect SoA. This indicates even higher-level factors of SoA should be considered.

1.2.2 Toward an interdisciplinary approach

Given the interaction between *human* and *computer* in HCI, an interdisciplinary approach is not only integral, but also mutually beneficial for psychology and computer science. In a seminal review, Limerick et al. (2014) posed this approach with regards to SoA, noting potential implications and applications for both fields. As a result of technological advancements in computer science, psychology stands to benefit from new ways of investigating SoA, thus gaining a better understanding of the underlying mechanisms. By the same token, computer science (more specifically HCI) can benefit from the theoretical and methodological developments in research on the psychology of SoA. These developments will offer better ways of quantifying and understanding user experience in this domain.

An added benefit of this interdisciplinary approach is the promise of greater conceptual clarity in the field of HCI. For example, latency is a salient topic of HCI research but can refer to different stages of an agentic chain. That is, latency is sometimes considered in the context of delays at the input stage of interaction (Berberian et al., 2013; Evangelou et al., 2021; Waltemate et al., 2016) and at other times in the form of delays at the outcome stage (Winkler et al., 2020). Both forms of latency are likely to be relevant for the SoA, but may have different effects. Another example is with SoA itself: at times it is referred to in the HCI literature as control over an action (Koilias et al., 2019), and at others it is used to refer to a broader concept that encompasses control over actions as well as outcomes (Cornelio et al., 2020). The involvement of experts from both fields will help to close these gaps and unify the literature, ultimately advancing the research.

Situating the research in theoretical frameworks of SoA could ensure stronger foundations. Williamson et al. (2009) states that a computer interface facilitates control by providing feedback of the system state and the user can use this comparison modify their input accordingly and predict state changes. Given the similarity to the comparator model of SoA, both could be mutually informed here. More recently, studies have included these theories within their framework. For example, Kokkinara et al. (2016) notes that while comparator mechanisms are typically considered, situational cues in conjunction with user intention also play a role. Using these principles, essentially from apparent mental causation, their experiment induced illusory SoA over a virtual body walking while physically seated. Evangelou et al. (2021) refers to the cue integration approach to explain their findings whereby visual cues tend to dominate the user's SoA experience until they become unreliable. Applying theoretical frameworks has recently been recognised by Legaspi et al. (2019) who note the limited use of models in artificial intelligence (AI). The authors reference a unified model (Figure 1.5) in a review on how AI can both draw knowledge from and is poised to inform our understanding of SoA.

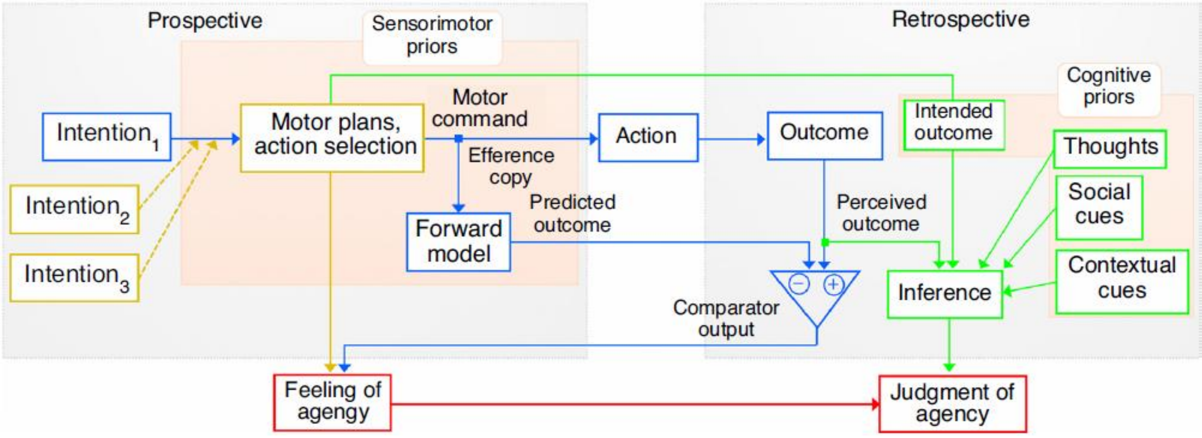

Figure 1.5*. Unified, comprehensive sense of agency model from Legaspi (2019).*

Perhaps the clearest and most substantial benefit of collaboration is in the methodology and measurement. Limerick et al. (2014) noted the particular application of the binding measure. Firstly, as a behavioural and quantitative measure of the *degree* of SoA. Secondly, as it is well suited to HCI due to the nature of ongoing, subsecond interaction loops. This method has indeed been applied in empirical HCI research (Bergstrom-Lehtovirta et al., 2018; Coyle et al., 2012; Deans-Browne et al., 2022; Limerick et al., 2015; Martinez et al., 2017; Z. Barlas, 2019). What has seldom been considered however, is the importance of using both implicit and explicit measures, utilised in some recent research (Evangelou et al., 2021; Winkler et al., 2020). Such methods provide a more comprehensive account of how the feeling and judgement of agency can and does differ. Additionally, by working more closely with computer scientists and HCI experts, psychologists stand to benefit from the expansion of paradigms. For example, technological advances permit more precise manipulation of sensory modalities which can be utilised to investigate SoA (Cornelio et al., 2021, 2020). Furthermore, the potential for alternative ways of capturing the binding measurement where necessary (Cornelio Martinez et al., 2018). More intricate experimental manipulations could contribute to a more nuanced understanding of the complex process that is SoA.

1.3 The role of haptics

Haptics refers to perception of touch and proprioception, and haptic technology artificially generates this for system interactions (Hannaford & Okamura, 2016). Such sensations are rendered in a variety of ways such as electro-tactile (Pamungkas & Ward, 2015), vibrotactile (Choi & Kuchenbecker, 2013) signals and more. Recent technological advances have even utilised ultrasonic waves to travel through the air and directly stimulate mechanoreceptors on the hand, creating touch sensation without physical contact (Georgiou et al., 2022). As actively generated sensations which convey information, here posits a role for haptics in bridging the gulfs by communicating the system state through touch. Employing psychological methods to understand this role stands to scientifically inform HCI. Moreover, as it is entirely additive feedback and can be manipulated, which offers fresh possibilities for psychological research.

1.3.1 Interest for HCI

For HCI, interest lies in how to optimally integrate haptics in a way that improves or preserves SoA. Research has shown this may depend on the input modality, and whether the haptic feedback is conveying information associated with actions or outcomes. For example, Martinez et al. (2017) found no significant differences in SoA between gesture-based and physical touch-based actions made. Rather, significant differences were shown between outcome-based sensory modalities, with mid-air haptics showing an increase in binding as compared to visual feedback in touchless interactions. Further to this, Evangelou et al. (2021) investigated mid-air haptics for touchless actions made in virtual environments. Results showed that haptics could increase intentional binding, but only at longer action-outcome intervals. Furthermore, in the absence of haptic feedback there was a loss of self-reported SoA when visual latency for the virtual hand movement was induced. However, this was not observed in the presence of haptic feedback, suggesting that haptics can protect against the negative impact of latency.

The effects of haptics may also depend on their coherence with other sensory modalities, and alignment with user intentions and expectations. Berger et al. (2018) refers to the "uncanny valley of haptics" whereby incongruent – even if overly *precise* as opposed to *imprecise* – haptics can elicit rejection from the user. Their study showed that in active conditions where the user has agency over these haptics, incongruent effects may be attenuated. The authors suggest that when actively triggering haptics, the user is provided with a causal explanation for these sensations and becomes more tolerant of sensory discrepancies. A study by Tajima et al. (2022) investigated the trade-offs between user -and computer-driven touch, and reveals a further level of complexity when it comes to haptics and SoA. They showed that the attribution of agency may depend on whether computer-driven touch causes outcomes aligned with the user's intention.

1.3.2 Interest for psychology

Research on the effects of haptics is also likely to be informative from a purely psychological perspective, helping to shed light on the mechanisms of SoA. For example, existing research in HCI is giving us an insight into the how haptic information may interact with other sensory modalities in the construction of SoA. As discussed above, research has shown how haptic information can act to maintain SoA under delays in visual feedback (Evangelou et al., 2021). Studies have also shown how haptics and other information contribute to both SoA and/or SoO. For example, synchronous visual feedback has been shown to be sufficient for both SoA and SoO over a virtual body (Krom et al., 2019), however the addition of vibrotactile feedback seems to mainly influence SoA (Banakou & Slater, 2014). Beyond these insights, research in the field of HCI is also benefitting the psychological study of agency through the developments of new technologies, like mid-air haptics. These open up exciting new possibilities in terms of paradigms and what we can manipulate, which, in turn, will help improve our understanding of SoA.

The use of haptics also extends to research and applications in clinical psychology and neurology. Research on schizophrenia suggests prediction errors may underly the disruption to SoA, which impair the attribution of action consequences (Voss et al., 2010). This has been extended in a study by (Foerster et al., 2021) looking at the effects volatile haptic feedback on SoA in patients with schizophrenia. Subliminal haptic delays during a pointing task impacted motor adaptation and feelings of control as compared to typical individuals. This suggests typically negligible feedback is aberrantly salient to patients with schizophrenia, resulting in prediction errors.

Another scope of haptic applications is motor rehabilitation. Studies have shown agency over visual feedback can facilitate performance (Miyawaki et al., 2019; Nataraj & Sanford, 2021), and even disproportionate positive feedback can increase both (Nataraj et al., 2020). Authors suggest positive implications for motor rehabilitation. Additionally, integrating synchronized haptics with visual feedback in virtual environments has been suggested to facilitate interaction with objects such as reaching, grasping and manipulating (Adamovich et al., 2009). Patton et al. (2006; 2006) tested the use of haptically augmented errors in a training task with stroke patients, showing post-training benefits were found for movement in a reaching task. Although no direct investigations, research alludes to a link between haptics, agency and performance that has positive implications for motor rehabilitation.

1.4 Rationale and lines of investigation

This chapter has laid the foundations for the work carried out with the overarching aim of investigating role of mid-air haptics in SoA. An interdisciplinary approach underlies this by applying psychological methods to ensure scientific rigour in the development of this technology and utilising this technology for novel exploration of the psychological concept.

With this principle in mind, I aim to cover a role for mid-air haptics in modulating SoA with the full process in mind, encompassing intention, action and effect. For action and effect, both implicit and explicit measures of agency will be used. The interval estimation paradigm (Engbert et al., 2008; Moore et al., 2009) will be adapted to use binding as an implicit measure. Previous research has captured differences at the explicit level by separating self-report questions of control over action from causal influence over outcome (Evangelou et al., 2021); this will be carried forward. For a measure of intention awareness, the classic Libet clock paradigm (Libet et al., 1983) will be adapted. Finally, theoretical accounts will be discussed when interpreting findings, as each experiment is designed with the underlying consideration of testing them.

The implications for HCI are fundamental to this project. As such, by and large the experiments throughout are driven by an applied context for mid-air haptics. Chapter 2 is situated within the context of virtual reality with a focus on action. A literature review sets the foundation for the concept of the virtual self, followed by two experiments looking at integrating mid-air haptics with visual elements. Chapter 3 is situated within the automotive context with a focus on feedback effects for a gesture-based user interface. A literature review will introduce SoA with regards to driving and the importance of dual-task consideration, followed by two experiments comparing sensory modalities and feedback meaning.

Chapter 4 takes a turn toward the intention aspect of SoA. The more fundamental concept of volition is introduced, giving insight into the literature on the will and voluntary action. Bearing similarity to theoretical accounts of agency, two experiments test whether volition is predictive, postdictive or integrative by manipulating (haptic) feedback reliability.

Finally, chapter 5 provides a general discussion of the work. Specific findings are expanded on and synthesised with reference to a comprehensive model of SoA. The implications for HCI are drawn in terms of practical applications. General limitations and future directions for research in this area are also considered.

Chapter 2

Haptics and the virtual self

2.1 Introduction

Virtual reality (VR) opens new possibilities for action and interaction. These technologies expand the horizons of human agency by allowing us to navigate virtual worlds with our own body movements (Seinfeld et al., 2020). Interactions in virtual worlds are not bound by physical laws which poses questions to the impact on the minimal sense of self regarding our body and the capacity to act. That is, the senses of ownership (SoO) and agency (SoA) (Gallagher, 2000). Sensory feedback from the environment is considered important for constructing and grounding the self in this sense (De Vignemont, 2013; Moore & Fletcher, 2012). Given its malleability, this psychological construct is relevant to bodily interactions in virtual environments.

Experimental psychology takes interest in the use of VR as it offers systematic manipulation of feedback which provides control and reproducibility (Pan & Hamilton, 2018). In parallel, computer-science recognises the benefits of applying psychological methods in VR research to understand user experience (Gonzalez-Franco & Peck, 2018). Accessibility and scope for VR continues to increase, including use for neurorehabilitation (Moreno et al., 2019), educational training (Wang et al., 2018), medicine (Pensieri & Pennacchini, 2014), and gaming and entertainment (Cruz-Neira et al., 2018). Considering these uses, understanding how to improve the virtual self and provide the user with SoA is critical.

In this chapter, first I review the relevant literature by 1) introducing SoA as a dissociable construct of the minimal self, 2) considering important factors as we move from physical to virtual and 3) build rationale on the role of haptics. I will then present two experiments investigating the role of haptics in modulating SoA during virtual interactions. Finally, I will discuss the findings and implications with the interdisciplinary perspective in mind.

2.2 The minimal self: the senses of agency and ownership

Irrespective of longer term narratives built about the self, is a basic sense of self as an immediate subject of experience, considered the minimal self (Gallagher, 2000). As such, this experience can also occur pre-reflectively. There is a phenomenological distinction at the level of minimal self-awareness, between SoO and SoA. The former can occur generally during bodily experiences such as those even passively generated, the latter however is intrinsically tied to action (Tsakiris & Haggard, 2005). The two experiences can interact as we often voluntarily act with our own body and so follows the typical experience that *I moved* (SoA) this with *my arm* (SoO). Notably however, they can be dissociated and may be independently investigated.

Experiencing a body as one's own is referred to as SoO, in the sense that this is not implied simply because one has a body and its associated sensations (Frederique De Vignemont, 2007). The key aspect here is a feeling of *mineness*, as Gallagher (2000) refers to the sense that it is *my* body undergoing the experience. Control and causation are key factors for SoA however, which refers to the *experience* of initiating action to exert causal influence (Moore, 2016). This is also a subjective experience in the sense it is not implied simply because we acted. Exemplars of this and their dissociation can be found in clinical cases demonstrating their impairment. Patients with somatoparaphrenia deny their paralyzed arm belongs to them even with somatosensory processing intact (Vallar & Ronchi, 2009). However, patients with anarchic hand syndrome recognise their affected hand as their own yet describe its actions to be against their will (Gallese & Sinigaglia, 2010). As such, SoA is a central yet distinctive component of the immediate sense of self by allowing to distinguish self -and other-generated actions.

To measure the feeling of owning a body does not require action and so experimental research for SoO can be passive for the participant. For example, the rubber hand illusion (RHI) is a widely used paradigm used to induce and measure SoO (Botvinick & Cohen, 1998; Costantini & Haggard, 2007; Ehrsson et al., 2005; van Stralen et al., 2013). A prosthetic hand is placed parallel to the hidden participants hand on the table and synchronous tactile information (brush stroke) is provided to both. Participants report experiencing the touch on the rubber hand as though it belongs to them and tend to displace their real and as closer to the prosthetic. The latter is considered an implicit measure termed proprioceptive drift. Notably, research has shown that while adding active elements can strengthen SoO (Dummer et al., 2009), it is not a necessary component (Walsh et al., 2011). Similarly, action-effect paradigms for measuring SoA do not necessarily require SoO. For example, in HCI where digital objects such as mouse cursors (Coyle et al., 2012) and spheres (Zopf et al., 2018) show SoA can be enhanced for non-bodily objects. Together, this illustrates the dissociation in methodology as well as factors of influence.

2.3 From physical to virtual

VR technologies allow one to be an active user in a virtual space with a virtual body which responds to their bodily movements in a precise manner (Freude et al., 2020). To do this, the virtual self must be represented in some way. Seinfeld et al. (2020) refer to this means of interaction as User Representation, stating the importance of appropriately mapping the user and their motor commands to that of the representation. More specifically to experiencing the bodily self, Pan and Hamilton (2018) emphasise synchronicity between visual and proprioceptive, motor, and/or tactile signals. That is, the virtual body being in line with the user's expectations of position, movement, and touch. These are examples of sensorimotor contingencies and are fundamental to the virtual self in that actions are carried out in accordance with such expectations (Slater, 2009).

Typically, our real-world movements and their relative visual feedback are one and the same (Lavoie & Chapman, 2021). This is a sensorimotor contingency developed and accustomed to over the lifespan, and therefore synchronous movement in virtual interactions is expectedly important for the virtual self. Studies have repeatedly shown avatar movement asynchronous with that of the user has a negative impact (Banakou & Slater, 2014; González-Franco et al., 2010; Lesur et al., 2018; Sanchez-Vives et al., 2010). Notably, SoA is more sensitive to visuomotor delays, breaking down with delays as low as 50-150ms (Evangelou et al., 2021; Koilias et al., 2019; Waltemate et al., 2016) as compared to SoO which is resilient until about half a second (Ismail & Shimada, 2016).

Our real-world interactions involving physical contact are typically accompanied with tactile feedback. Such visuotactile contingencies are also developed early in the lifespan and particularly sensitive to morphological characteristics of the body (Zmyj et al., 2011). It follows that this becomes important to grounding the virtual bodily self. Of course, the well-established RHI principles (synchronous visual-tactile brush stroke) were applied in early virtual hand illusion (VHI) studies (Slater et al., 2008). The addition of tactile feedback has even been shown to induce illusory SoA whereby vibrotactile feedback applied to the neck while an avatar is speaking leads participants to attribute the speech to themselves (Banakou & Slater, 2014).

As the practical applications of VR are increasing, including educational and clinical settings as well as entertainment (Chen, 2016; Garrett et al., 2018; Jensen & Konradsen, 2018), understanding the relationship between the virtual self and behaviour in these environments is important. For example, research suggests SoA influences presence, motivation and engagement (Seth et al., 2012), and such variables are vital to getting the most out of virtual environments. Having active control over a self-avatar also improves spatial rotation and memory performance whereby appropriate sensorimotor contingencies reduce cognitive load (Steed et al., 2016). Thus, appropriate self-avatar representation that gives the user a SoA could be beneficial for educational and training environments. The effects of experimentally inducing an illusory virtual self-experience extend to clinical settings. For example, inducing an active VHI can improve hand-eye coordination (Matsumiya, 2021). Furthermore, inducing a virtual walking illusion can even reduce neuropathic pain in paraplegic patients, as compared to just guided imagery or film viewing, for up to 3 weeks (Moseley, 2007), and up to 12 weeks in combination with transcranial direct current stimulation (tDCS) (Soler et al., 2010). Evidently, experiencing SoA with the virtual self may therefore play a crucial role for shaping motor performance and be beneficial for rehabilitation.

Conceptually in VR research, SoA and SoO, along with other constructs such as presence, are often referred to and studied as part of a whole – embodiment (Bovet et al., 2018; Debarba et al., 2017; Gonzalez-Franco & Peck, 2018; Kilteni et al., 2012). However, in doing so, studies are often constrained not only to self-report, but also to an incomplete scale for each independent construct. As illustrated in the above sections, while SoA and SoO are both central components of the self, they're very much dissociable and have extensively different experimental methods. With the interdisciplinary approach, I note the importance of separate, more thorough investigation into these variables. Breaking down experiments to allow for rigorous methodological paradigms may reveal effects at the implicit and/or explicit level. This is the approach here regarding SoA in virtual interactions.

2.4 The virtual agent: the role of mid-air haptics

Many VR applications depend on the user interacting with a virtual object in an immersive or non-immersive environment. An important consideration is the means of this interaction. One option is through a physical device such as a controller, or a wearable device that can track the user's movements. Another option is through hand-tracking which allows the user to directly interact with virtual environments and has been suggested to be a more naturalistic mode of interaction (Kangas et al., 2022). Although preferable in this manner, there are concerns about its accuracy and precision. This is particularly relevant when it comes to SoA, which is known to be acutely sensitive to perturbations in the relationship between a movement and its visual representation (Farrer et al., 2001, 2008). This feature of agency processing is captured by the comparator model, which emphasises the importance of a correspondence between expected and actual action feedback in generating the SoA (Frith et al., 2000).

In line with this, an extensive body of research has already confirmed that the relationship between user and avatar movement is important for the experience of agency. For example, artefacts such as latency, jitter and spatial congruency that disrupt the user-avatar relationship have been shown to impact SoA (Evangelou et al., 2021; Koilias et al., 2019; Ma et al., 2021; Roth & Latoschik, 2020; Seinfeld & Müller, 2020; Toothman & Neff, 2019). What has seldom been investigated, however, is whether the importance of sensorimotor contingency extends to our interactions with *objects* in the virtual environment. This is something explored here, by assessing the effect of manipulating the relationship between a virtual action aimed at an object and the behaviour of that object. Psychological theories have consistently emphasised the importance of environmental feedback in informing SoA (Moore & Fletcher, 2012; Wegner & Sparrow, 2004), and the limited research in this area would appear to support this. For example, it has been shown that when causing an object to move on a screen via a mouse click, the extent of the movement in terms of its congruency with the force applied can impact SoA (Lafleur et al., 2020). It can be expected that this extends to VR, where disruption of a virtual action-object relationship reduces SoA.

Another variable of interest in the context of hand-tracking technology is haptics. Although hand-tracking technologies allow for more naturalistic interactions, there is a lack of tactile feedback that would typically accompany actions in the physical world. Psychological theories of SoA emphasise the importance of bodily feedback and sensory signals in the construction of this experience (Moore & Fletcher, 2012; Wegner & Sparrow, 2004). In this way, the absence of haptic feedback would potentially harm SoA. Mid-air haptic feedback shows promise in overcoming this without the need for wearables or physical objects (Carter et al., 2013; Hoshi et al., 2010).

Cornelio-Martinez et al. (2017) demonstrated mid-air haptic feedback for gesture-based touchless interactions to be beneficial, increasing SoA as compared to visual. Recent research by Evangelou et al. (2021) has looked at the presence of mid-air haptics for virtual objects of interaction and shown this to optimise SoA under certain conditions. Moreover, their study demonstrated that the presence of this haptic information also protects against the loss of SoA arising from user-avatar latency. This latter finding is important in the present context as it suggests that any putative disruption of the avatar-object relationship with hand-tracking could also be mitigated by the presence of mid-air haptics.

2.5 Experiment 1

In light of the above, less is understood about the impact of the avatar-object relationship – behaviour of the object contingent on the virtual avatar's interaction – on SoA. The present experiment explores a) the effect of disruption to the avatar-object relationship, and b) its possible mitigation by haptic feedback in a non-immersive virtual environment. With this, the aim is to contribute to HCI by looking at whether the responsiveness of virtual objects affects SoA, and whether the positive effects of mid-air haptics extend from the user-avatar relationship to the avatar-object relationship. Moreover, to continue the interdisciplinary approach by using rigorous theory and methods from psychology to scientifically inform HCI. On the other hand, we also aim to further psychological understanding of agency processing by harnessing virtual reality and mid-air haptics to explore, in unique ways, the effect of sensory manipulations on SoA.

Participants pressed a virtual button with their avatar hand, which caused an auditory tone after a brief delay. In a visually congruent condition, the virtual hand made contact with the button which caused it to visibly depress. In an incongruent condition, the button did not visibly depress when the avatar hand made contact with it. The button press interaction was either accompanied with haptic feedback emulating a physical button press or no feedback at all. We measured SoA via the interval estimation paradigm (Engbert et al., 2008). This is an implicit measure of SoA based on changes in time perception associated with voluntary actions (button press) and effects (auditory tone). More specifically, when someone feels in control of their action and its effect, they perceive a compression of time between the two, referred to as intentional binding (Haggard et al., 2002; Moore & Obhi, 2012). We supplemented the binding measure with explicit self-report measures of agency, whereby participants were asked to rate their feelings of controlling the button press and causing the tone outcome. These questions are adapted from previous research (Evangelou et al., 2021) and tailored to the task.

We predicted a reduction in SoA in the visually incongruent condition. We predicted that the presence of haptic feedback would be associated stronger SoA than its absence. We also predicted that the presence of haptic feedback would interact with visual congruence, attenuating the reduction in SoA associated with disruption of the avatar-object relationship.

2.5.1 Method

This study received ethical approval from the Goldsmiths, University of London's ethics committee and carried out in-line with local Covid-19 regulations that were in place at the time.

Participants

Based on a medium effect size (f = .25) and desired power of .9, using G*Power (Faul et al., 2007) we calculated the required sample size to be 30 participants. In total, we recruited 32 participants (18 females, 1 prefer not to say) via email or the SONA participation database. They received a compensatory £15 Amazon voucher for their participation. Ages ranged from 18-50 years (*M* = 30.2 years; *SD* = 7.8 years). Two participants were excluded from analyses due to not following instructions (time estimates exceeding the maximum of that instructed) or too many unreported missing trials demonstrating a lack of concentration. Handedness was measured via the short form revised Edinburgh Handedness Inventory (Veale, 2014) to ensure that the dominant hand was used. For mixed handers (scores ranging 60 to -60) their self-reported preferred hand was used. There were no reported visual or hearing impairments.

Materials and apparatus

An interactive non-immersive virtual scene (see Figure 2.1a) was setup and run via Unity game engine (v2019.4.12f1). There was a virtual button and a virtual hand displayed on the screen. A Leap Motion camera was used to track the participants' hand movements, which were displayed on the screen as movements of the virtual hand towards the virtual button. The Leap Motion camera was attached to an Ultraleap STRATOS Xplore development kit which uses ultrasound technology to transmit tactile sensations directly to the hand (Carter et al., 2013). This was used to provide haptic feedback for the button press (see Figure 2.1b). The sensation for the button was designed to emulate a physical button force, with a circle shaped sensation that ranged dynamically from maximum intensity at the tip down to no feedback at the point of click, and back up.

A 14” HD monitor was used to display the virtual hand and button. The Ultraleap device was positioned so that the participant’s dominant hand would be tracked at a similar height to the desk (see Figure 2.1a). This allowed for a more naturalised button-press interaction. The pressing of the virtual button was followed by an auditory tone after a variable delay. One second later a UI panel was displayed on the screen, which could be interacted with via keyboard and mouse. Headphones were used to minimise the possible sensory conflict between the mid-air tactile sensation and the auditory noise generated by the ultrasound array.

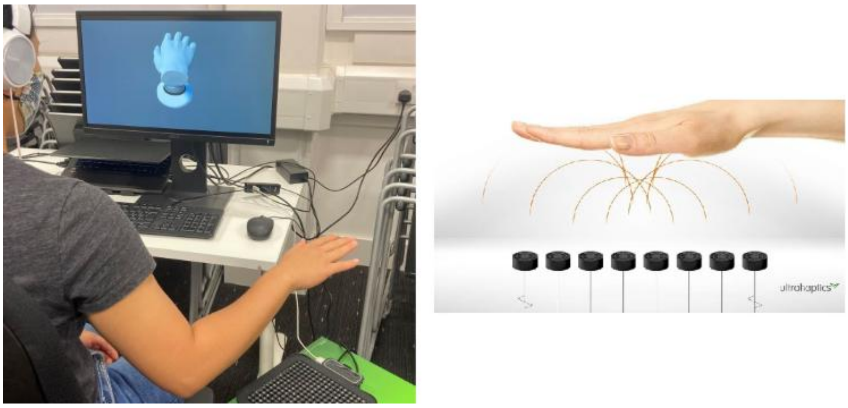

***Figure 2.1**. a) Experimental setup. b) visualisation of mid-air haptics*

Tasks and measures

To measure intentional binding (implicit SoA), we adopted the direct interval estimation method from Moore et al. (Moore et al., 2009). Participants were told that the interval between the button press and the tone would vary randomly between 1ms and 999ms. In reality, however, only three intervals are presented: 100ms, 400ms or 700ms in a pseudorandomised order. Participants entered their estimations manually in the UI panel and clicked to submit and continue for each trial. Shorter interval estimations are taken to indicate a stronger SoA.

For explicit SoA, two questions were adapted from previous work (Evangelou et al., 2021) and tailored to the task: “I feel in control of the button press” for control over intentional action and “I feel I am causing the tone by pressing the button” for causation of the outcome. These were measured on a Likert scale of 1 (strongly disagree) to 7 (strongly agree) and reported every 12 trials (3 times per condition), thus higher average scores represent greater explicit agency.

Design

We used a 2 (haptic feedback) x 2 (visual congruence) within-subject design. Haptic feedback was manipulated at two levels: with or without. Visual congruence was also manipulated at two levels: the button would depress with the movement of the virtual hand (Figure 2.2a) or it would remain fixed (Figure 2.2b). Each 36-trial condition was split into three steps. Each step consisted of 12 trials with the three interval lengths presented in a pseudorandomised order. At the end of each step we collected the self-report measures. A Latin square method was used to counterbalance conditions across participants.

Procedure

Participants were told they would be interacting with a non-immersive virtual scene, using a hand tracking system, where they would press a button and hear a tone after a short delay. They were required to estimate the time interval between when the button is pressed and when they hear the tone, and that this can vary between 1-999ms.

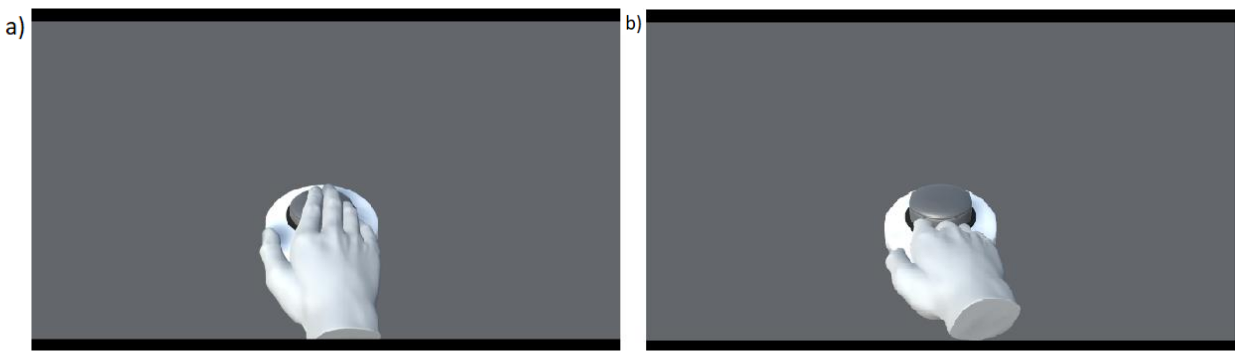

Figure 2.2. *a) Congruent visual feedback of button press. b) Incongruent*

For the learning phase, participants were sat at a safe distance from the monitor, put the headphones on and the Ultraleap apparatus was adjusted to a point that it was in a natural position. In this practice block, they would hover their hand over the ultrasound array to enter the virtual environment then press the button by making a downward movement of their hand. This triggered a tone after a brief delay. The screen paused 1s after the tone, allowing the participant to enter their estimate in the "*Enter milliseconds*" UI panel via the keyboard. Following this they clicked submit via mouse. On these practice trials only they also received feedback of the exact time delay. These time delays were all either 50ms, 500ms and 950ms to give them an idea of the lower, middle and far end of the scale. This block consisted of 10 trials with haptic feedback and visual congruence so as to also familiarise participants with the technology. In this time, participants were also instructed to try and avoid pressing the button twice in a single trial as this would render the trial void. If this did occur they were to report this and enter 0.

Moving onto the experimental block (Figure 2.3), it was reiterated to participants that intervals would now range from 1-999ms. They then completed 36 trials per condition, split into three blocks of 12 trials. After each block, an additional UI panel opened with each self-report question consecutively, and participants were told to click the answer (1-7, 1 being strongly disagree and 7 being strongly agree) that best indicates their experience. They then clicked continue in order to proceed to the next block of trials. A message was displayed to signal the end of a condition, after which participants were permitted a two minute break if necessary.

When the session finished, participants were debriefed and asked if they had any questions or if they noticed anything about the experiment.

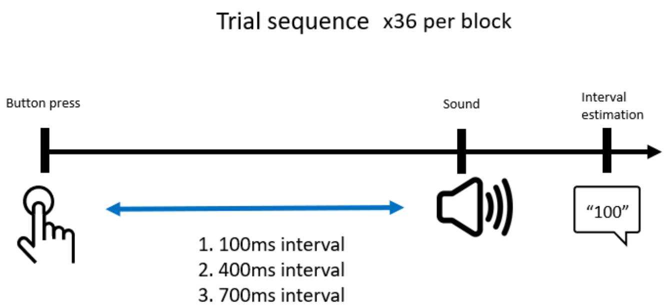

Figure 2.3. *Visualisation of a typical experimental trial within a block. Actual intervals pseudorandomised for 12 trials x3 for block step measure.*

2.5.2 Results

One participant was removed from the intentional binding analysis due to reporting losing concentration in one condition which led to consistent input of under 100ms. No outliers were detected (all $Z<3$). Interval estimations were averaged for each condition. *Lower* scores indicate *greater* binding, and therefore, stronger implicit SoA. Scores for self-reported *control* and *causation* were averaged for each condition separately, with *higher* scores indicating *greater* explicit SoA. Data were processed in Excel and analysis carried out in Jamovi 2 and R.

Haptics and visual congruence on interval estimations

A 2x2 repeated measures ANOVA with haptic feedback (with or without) and visual congruence (congruent or incongruent) was performed on interval estimations. There was no significant main effect of haptic feedback, $F(1, 28) = 0.38$, $p=.541$, nor visual congruence, $F(1, 28) = 0.80$, $p=.379$. In addition, while the haptic x congruence interaction demonstrated a marginal trend, the effect was non-significant, $F(1, 28) = 3.83$, $p=.077$, $\eta_p^2 = .11$ (Figure 2.4). Overall, this suggests that neither haptics nor visual congruence significantly influenced implicit SoA.

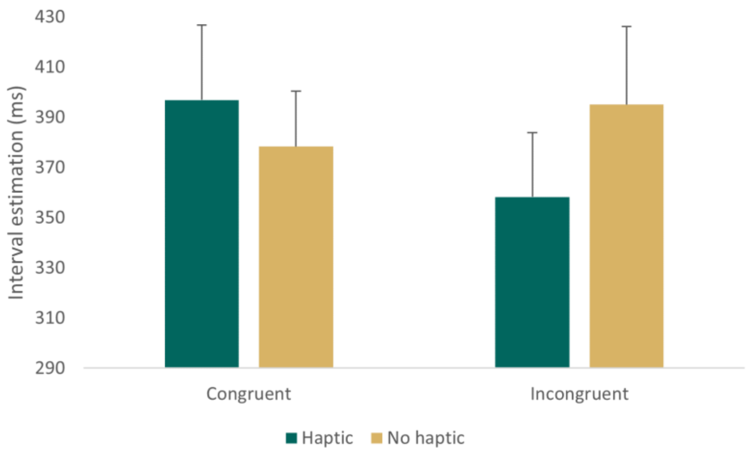

Figure 2.4. *Mean interval estimations plotted as a function of visual congruence and haptic feedback. The error bars represent standard error across participants.*

Haptics and visual congruence on self-reported control and causal influence

Due to significant departures from normality in the self-report data (Shapiro Wilk, $p<.05$, Skewness Z>1.96), we applied the aligned rank transform (ART; (Wobbrock et al., 2011)) before conducting the ANOVAs. This method permits factorial ANOVA on non-parametric data to also examine interactions.

A 2x2 repeated measures ANOVA was conducted on the aligned ranks for self-reported control with haptic feedback (with or without) and visual congruence (congruent or incongruent) entered as within-subject factors (Figure 2.5). There was a main effect of haptic feedback, $F(1, 87) = 18.78$, $p<.001$, $\eta_p^2 = .18$, such that feelings of control over the button press

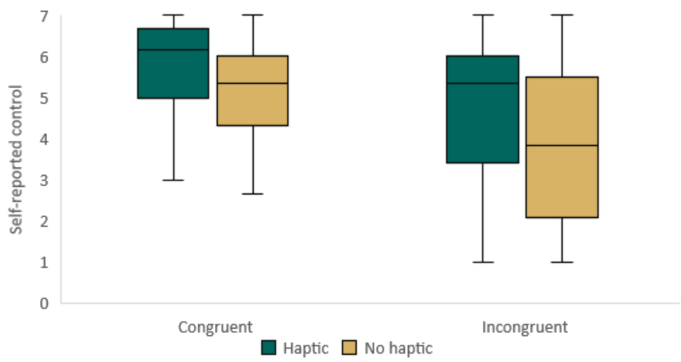

Figure 2.5. *Ratings of control over the virtual button plotted as a function of visual congruence and haptic feedback. The middle lines of the boxplot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile*

action were greater with haptic feedback than without. There was also a main effect of visual congruence, $F(1, 87) = 30.46$, $p<.001$, $\eta_p^2 = .26$, revealing a greater sense of control over action when the button press was congruent compared to when not. There was no significant interaction, $F(1, 87) = 0.65$, $p=.422$, and so post-hoc tests were not carried out.

A 2x2 repeated measures ANOVA was conducted on the aligned ranks for self-reported causation with haptic feedback(with or without) and visual congruence (congruent or incongruent) entered as within-subject factors (Figure 2.6). There was a main effect of haptic feedback, $F(1, 87) = 5.26$, $p=.024$, $\eta_p^2 = .06$, such that feelings of causing the outcome were greater with haptic feedback than without. There was also a main effect of visual congruence, $F(1, 87) = 9.17$, $p=.003$, $\eta_p^2 = .10$, revealing a greater sense of causal influence when the button press was congruent compared to when not. There was no significant interaction, $F(1, 87) = 0.07$, $p=.785$, and so post-hoc tests were not carried out.

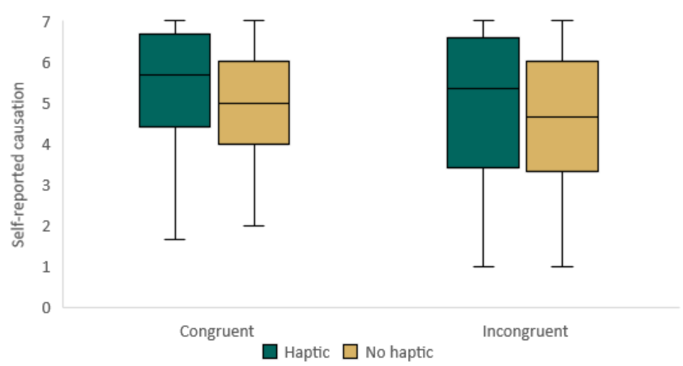

Figure 2.6. *Ratings of causal influence over the tone plotted as a function of visual congruence and haptic feedback. The middle lines of the boxplot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range minimum or maximum*

Interim Summary

Together, these findings suggests that the addition of haptic feedback when interacting with a virtual object does increase explicit but not implicit SoA. However, it does not protect against the negative impact of visually incongruent avatar-object behaviour.

2.6 Experiment 2

Experiment 1 focused on the presence and absence of mid-air haptics and the congruence of visual feedback. What is yet to be investigated is how varying types of haptic information may impact SoA. Mid-air haptics is an additive source of sensory information and so may not need to be in congruence with how a physical object would feel, instead favouring precision. Previous literature suggests haptics should be rendered in concordance with other sensory feedback (e.g. visual) as increasing the fidelity past this can create conflict in the subjective illusion of realism (Berger et al., 2018). The authors also note this is more impactful for passive haptics, and that having agency over the haptic interaction would attenuate this conflict due to providing causal explanation. However, what is not clear is how differences in haptic rendering could impact the experience of SoA *itself*.

Here, we explore whether different types of mid-air haptic feedback accompanying a virtual button press affects SoA. We kept the visual information congruent and manipulated the mid-air haptics accompanying the button press to either be *dynamic*, *fixed*, *on press-completion only*, or *no feedback* at all. If precision is more important to SoA, there should be no difference between the haptic conditions as all are precise in their function. If congruence is more important over and above precision, the dynamic condition should increase SoA as it emulates the visual elements more accurately.

2.6.1 Method

Participants

Based on a previous study (Evangelou et al., 2021), 32 participants were required for 0.8 power. Thus, 39 participants were recruited from Goldsmiths University; these were 1st year

Psychology students and received course credits as part of their research participation scheme. 4 were excluded due to issues with the task, leaving 35 (27 females) for the analysis. Ages ranged from 18-32 (*M*=20.4; *SD*=3.5). Handedness was measured via the short form revised Edinburgh Handedness Inventory (Veale, 2014) to ensure dominant hand was used; for mixed handers (scores ranging 60 to -60) their reportedly preferred hand for the task was used. There were no reported visual or hearing impairments.

Materials and apparatus

An interactive non-immersive virtual scene (see Figure 2.7) was setup and run via Unity game engine (v2019.4.12f1). A Leap Motion camera enabled the hand to be tracked and to interact with a virtual button and was attached to an Ultraleap STRATOS Explore (USX) development kit in its standard configuration. The USX device utilises ultrasound technology to transmit tactile sensations directly to the hand (Carter et al., 2013), and provided haptic feedback for the virtual button (Figure 2.8b). A haptic sensation for the button was designed for each condition (Figure 2.8a): *dynamic* which ranges in intensity to match the depress of the button; *fixed* max intensity when in contact with the button; 300ms burst of max intensity only at the point of click *completion*; and finally, no haptics. All haptic conditions were rendered through spatiotemporal modulation (STM) of a high intensity ultrasound focus moving round a 5cm perimeter circle at 8m/s (Frier et al., 2018).

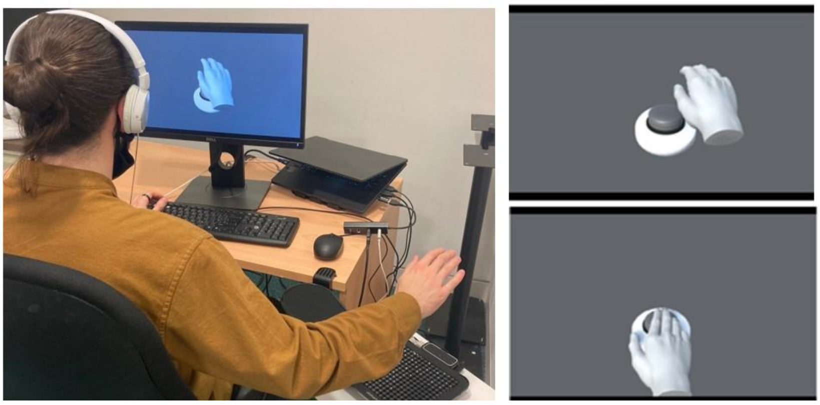

Figure 2.7. *Apparatus setup and virtual scene perspective*

A 14" HD monitor was used with participants sitting at an appropriate distance from it along with an arm rest on the side of their dominant hand. The USX device was positioned where the hand is tracked at a similar height to where the hand would rest on a desk. This allowed for a more naturalised button-press interaction. The pressing of the virtual button was followed by an auditory tone and 1s later a graphical user interface (GUI) panel which could be interacted with via keyboard and mouse. Over-the-ear headphones were used to minimise the possible conflict between the ultrasound audibility and the mid-air haptic tactility.

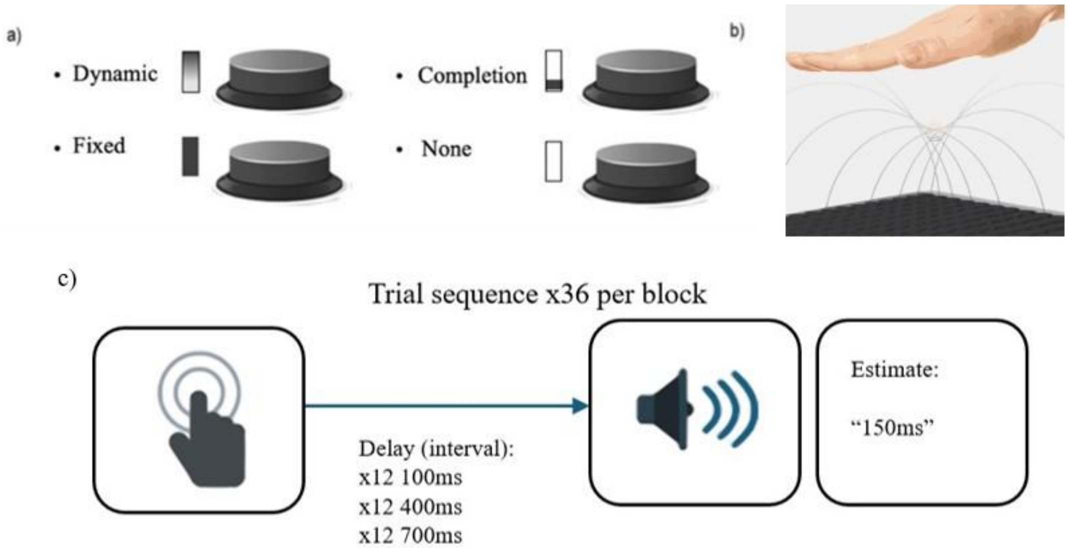

Figure 2.8. *a) Mid-air haptic types b) Representation of mid-air haptics c) Experimental block and trial structure*

Measures

To measure implicit SoA, we used the interval estimation version of the intentional binding paradigm (Engbert et al., 2008). Here, participants are required to directly estimate the interval between action and outcome. Following the standard format, intervals between the point of click and the auditory tone varied pseudorandomly at either 100ms, 400ms or 700ms (Figure 2.8c), while participants were told the range could be from 1-1000ms. Shorter interval estimates are taken to indicate a stronger SoA (Moore & Obhi, 2012).

As an explicit measure of agency, rating scales can be used to have the participant directly report their judgements of the amount of agency in an interaction. Two questions were adapted from Evangelou et al. (Evangelou et al., 2021) and tailored to the task: "I feel in control of the button press" for control over the interactive object and "I feel I am causing the tone by pressing the button" for causal influence over the effects. These were measured on a Likert scale of 1 (strongly disagree) to 7 (strongly agree).

Design and procedure

A within-subjects design was used with all participants completing all 4 conditions of haptic feedback (dynamic, fixed, completion, no feedback). Each block was a different condition, and these were counterbalanced using the Latin Square method to account for order effects. There were 36 trials per block and each interval was played 12 times each in a random fashion (Figure 2.8c).

Participants were told they will be interacting with a non-immersive virtual scene via a hand-tracking system that can provide haptic feedback to their hand. Their task will be to press a virtual button which will be followed by a short tone, and that there will be a time delay between the click of the button and the tone. This time delay will vary from 1-1000ms, and they will be required to estimate this interval.

They were sitting at an appropriate distance from the monitor and wore headphones. There was also an arm rest to which they found a comfortable position to leave their arm over the array to minimise full arm movement and fatigue while maximising comfort. 1s after the tone played, the GUI screen opens prompting to submit their estimate using a keyboard, before pressing continue to start the next trial. Participants were told that in each trial, they can press the button whenever they choose. Very rarely, the tracking camera would miscalibrate and pressed the button before the virtual hand was in view, rendering a trial void (<1% trials).

For the learning phase, participants first completed a practice block of 10 trials with no haptic feedback. The intervals varied randomly between 50-950ms (in multiples of 50) and were displayed to the participant to give them an idea of the millisecond timescale. This practice block also gave participants an introduction to the task and use of the system.

In the experimental blocks, participants were given 5 practice trials before starting to remove any initial surprise of the haptic condition. Self-reported agency was taken twice per block (every 18 trials) to sustain attention and also for extra measure. This was via a different UI screen with the question on the screen and participants clicked anywhere from 1 (strongly disagree) to 7 (strongly agree). An "End of block" message was displayed at the end of each block; participants were permitted a 2min break in between blocks if necessary.

When the session finished, participants were debriefed and asked if they had any questions or if they noticed anything about the experiment.

2.6.2 Results

Interval estimations were averaged for each condition respectively so that *lower* scores indicate *greater* agency. Scores for self-reported control and causation were averaged separately, and for each condition respectively, with *higher* scores indicating *greater* agency. There were no sex differences in interval estimations nor self-report measures (all $p>.05$); age also did not correlate with any of the measures (all $p>.05$). There were significant departures from normality in two interval estimation conditions and all self-report measures (Shapiro Wilk, $p<.05$, Skewness $Z>1.96$); while removing outliers may alleviate this, none were found (all $z<3.29$, MD>.001). Therefore, non-parametric tests were used across the board. Data was processed in excel and analysis carried out in Jamovi 2.

Effect sizes (Kendall's W value) were calculated as follows:

$$W = \frac{\chi 2}{N(\mathrm{p}-1)}$$

where χ^2 is the test statistic, N is the total sample size and p – 1 is the degrees of freedom (Morse, 1999). Holm-Bonferroni corrections for Durbin-Conover post-hoc tests set alpha level to:

$$\alpha = .05/(m - k + 1)$$

where m is the number of tests and k is the rank of the p value.

Haptics feedback on interval estimations

A Friedman test of repeated measures was carried out on interval estimates with 4 conditions of haptic feedback (dynamic, fixed, completion, and no feedback). There was a significant effect, $\chi^2(3) = 13.05$, $p=.005$, $W=0.12$ (Figure 2.9), such that interval estimations varied as a function of haptic feedback. Durbin-Conover post-hoc analyses showed this was driven by significant differences between no haptics and completion haptics ($p<.001$), and no haptics and fixed haptics ($p=.007$). While there appeared to be a marginal difference between dynamic haptics and completion haptics ($p=.021$), this was non-significant. No other differences were found.

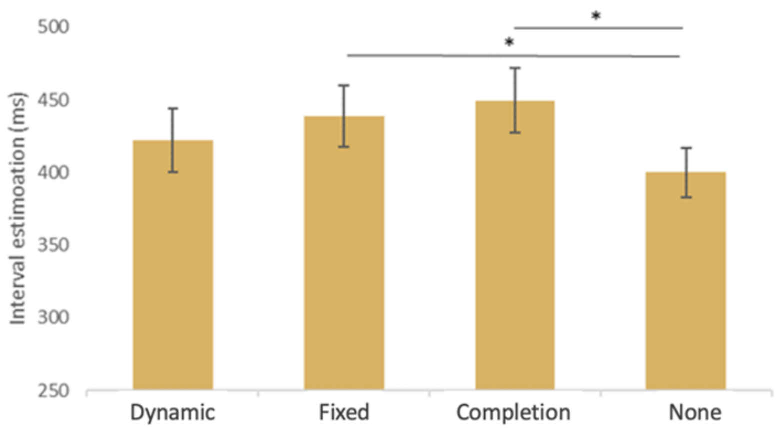

Figure 2.98. *Mean interval estimations per condition. Lower scores indicate greater agency. Error bars represent standard error across participants..*

Haptics feedback on self-reported agency

A Friedman test of repeated measures showed no significant differences in self-reported control between conditions of haptic feedback (Figure 2.10a), $\chi^2(3) = 0.69$, p=.876. Post-hoc tests were not carried out.

A Friedman test of repeated measures showed no significant differences in self-reported causation between conditions of haptic feedback (Figure 2.10b), $\chi^2(3) = 3.86$, p=.277. Post-hoc tests were not carried out.

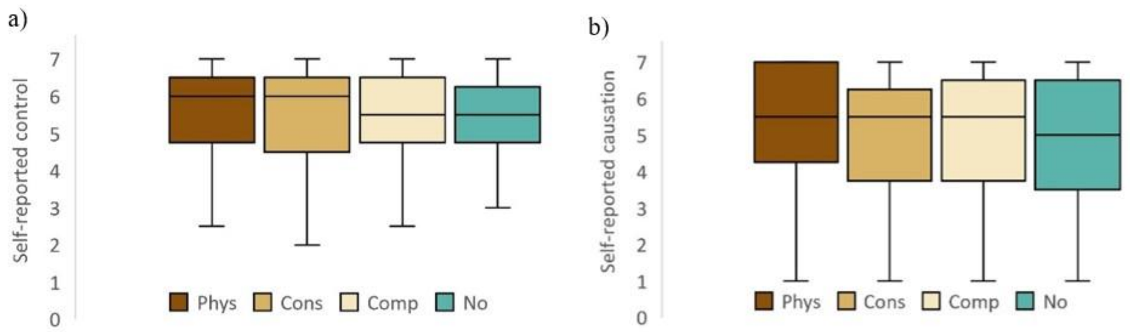

***Figure 2.10**. Ratings of a) control over the button press and b) causal influence over the tone plotted as a function of mid-air haptic type. The middle lines of the boxplot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range or minimum or maximum.*

Interim Summary

These findings suggest different mid-air haptic types influence implicit but not explicit SoA. More specifically, when the haptics does not emulate a physical button press in accordance with the visual feedback, there is a negative impact.

2.7 Discussion

We investigated the effects of integrating mid-air haptics into VR interactions on the user's SoA. The findings generally showed that external sensory feedback can impact SoA even when all actions are made voluntarily. Loss of haptics and also visual incongruence particularly impact explicit judgements, but further subtle mid-air haptic differences modulate this at the implicit level.

The lack of a significant effect on implicit SoA in Experiment 1 is surprising, especially given the apparent importance of these variables for SoA (Evangelou et al., 2021; Farrer et al., 2008; Limerick et al., 2014; Wegner & Sparrow, 2004). There was a marginal trend in the interaction however, notably a more positive effect of haptics under visual incongruence. As a cautionary explanation, it could be that the consistent presence of reliable internal motor signals (e.g. Moore & Haggard, 2008; Moore et al., 2009) simply attenuated any effects. The effects on explicit SoA extend previous literature which has shown a particular impact on self-reported control over action but not of causing the outcome (Evangelou et al., 2021). Notably here, both were impacted - positively by haptics and negatively by visual incongruence. This shows that the response of an object of interaction not only effects how the user feels in control of the action but extends to their judgements of causal influence over the following effects.

Results from Experiment 2 showed that different mid-air haptic types can modulate and even negatively impact implicit SoA. Previous literature states that having agency over a haptically incongruent event overcomes any negative effects on user experience (Berger et al., 2018). Our study offers a slightly different perspective on this issue, suggesting that haptic incongruence can negatively affect the user's implicit SoA over the interaction itself. In our study, even though the fixed and completion haptics were precise in their function, they did not match visual depression of the button, and as such, there was haptic incongruence. The effect of this was to reduce the SoA, revealing a negative effect on user experience. Intriguingly, these effects were only evident at the implicit level and participants reported no differences.

It has been suggested that implicit and explicit aspects of SoA are influenced by different agency cues (Synofzik et al., 2008). Implicit levels rely more on sensorimotor signals and explicit levels more on external sensory feedback. Moreover, that these reflect differences in the feeling and judgement of agency, respectively. In this way, more obvious visual and haptic differences are salient (present/absent) and therefore available as explicit judgements to the user, while more subtle haptic differences (dynamic/constant/completion) have an implicit influence below the level of awareness. Research has demonstrated a close link between haptic feedback and the sensorimotor loop whereby it facilitates online modulation of movement intention (Gomez-Rodriguez et al., 2011). Evidence also suggests small discrepancies affecting motor signals do not always reach conscious awareness (Castiello et al., 1991; Fourneret & Jeannerod, 1998). It may be therefore that these smaller haptic differences are indeed affecting the feeling of agency.

Cautionary to the above speculation, however, is that experiment 2 did not find self-reported ratings of SoA to be significantly lower in the no-haptic condition (a would-be salient present/absence difference) as in experiment 1. This could be due to an experimental design difference whereby experiment 1 was a factorial design, and the no-haptic impact was driven more by the visual incongruence condition. However, this is unlikely as there was no interaction effect. As such, it may be just a more powerful analysis – again due to the factorial design – of a haptic presence/absence main effect in experiment 1, masked by the different haptic conditions in experiment 2.

It is arguable that across the two experiments there is a general lack of binding as most interval estimations do not fall very far below 400ms (a would-be baseline of 0). One explanation of this is that actions in the virtual world are seen as effects of movements in the physical world, and that the auditory tone effect that follows is seen as a second effect. Research has shown that while binding can occur for a second effect in an agentic chain, it does get significantly weaker (Ruess, Thomaschke, Haering, et al., 2018). However, much previous research in VR has shown evidence for the binding effect (Evangelou et al., 2021; Kong et al., 2017; Winkler et al., 2020; Zopf et al., 2018). An alternative view then is that more work is needed in appropriately integrating mid-air haptics with already available visual information in VR. For example, this may have demonstrated an uncanny valley effect whereby we are sensitive to discordant virtualisation of the senses (D'Alonzo et al., 2019). That is, in an attempt to recreate the physical world in VR, our fine-tuned sensory perception is particularly susceptible to even subtle incongruence. The SoA processing system then, particularly the implicit feeling, has difficulty justifying the integrated feedback it is getting (Berger et al., 2018).

This has implications for mid-air haptics in VR in that there is potentially some way to go in terms of improvement for the user's feeling of SoA. However, there was generally no loss of agency in the congruent conditions. Given mid-air haptics has been shown to improve other user experience factors such as engagement (Limerick et al., 2019), enjoyment (Hwang et al., 2017) and presence (Seth et al., 2012), its appropriate integration is evidently beneficial overall. Additionally, these findings illustrate the importance of rigorous scientific method which can capture subjective experience at the implicit level as well as explicit.

In terms of the user attributing themselves as an agent in the interaction, these findings show that visual congruence can impact this. This confirms the importance of this factor and this should be salient when designing interactive virtual objects. Future research could also look into the extent of these effects too, for example whether more recent physics-based hand-object interactions (Oberweger et al., 2018) actually strengthens agency. We also extend previous suggestions that the influence of mid-air haptics may be limited to protecting explicit feelings of control under conditions of agentic uncertainty (Evangelou et al., 2021). Our data here suggests the presence of haptics can generally strengthen both explicit control over objects and the resulting causal influence.

One limitation we consider here concerns the minimal self-report data collected. This limited the scope both of understanding the relationship to the perception of the mid-air haptics and also the broader relationship to the minimal self. For example, when participants were asked about their experience after the experiments, most were fully aware of the visual incongruence in Experiment 1 (where explicit SoA was affected). However, with the subtle mid-air haptic differences in Experiment 2 (where implicit SoA was affected) they generally stated potential differences but could not confirm exactly what the differences were. By including this as an official measure, this could account for differences in awareness and contribute to the theoretical difference between explicit and implicit SoA.

Another limitation relates to the non-immersive virtual environment. While this is appropriate for our aim here (i.e. an examination of SoA in a simple virtual object interaction), it does limit the scope of its broader significance when it comes to HCI applications. For example, it would be interesting to note whether these effects extend to or even change in an immersive virtual environment. Despite this limitation, it should be noted that previous research has shown that implicit and explicit SoA are not affected by such a change of display modality (Winkler et al., 2020).

Finally, a lack of a passive control condition in our in these experiments could be considered a limitation. Although our design allowed for the relative comparison of sense of agency between conditions as widely used in previous studies (Barlas & Kopp, 2018; Bergstrom-Lehtovirta et al., 2018; Coyle et al., 2012; Winkler et al., 2020), a passive control condition would have permitted stronger claims regarding the absolute presence or absence of sense of agency (Bednark et al., 2015; Cravo et al., 2009). This is particularly important regarding the aforementioned speculations on the lack of binding in VR. For example, rather than referring to 400ms as a would-be baseline, a passive condition could be used as a more accurate within-experiment baseline, allowing for a stronger absence-of-SoA claim.

In sum, these studies provide novel investigation into the user's SoA during mid-air haptic virtual interactions. We show that the addition of congruent mid-air haptic feedback into a virtual button press can ensure user’s report a greater SoA at the higher level. However, we also show that potentially perceived-to-be incongruent mid-air haptics – not reported at the higher level – can result in a loss of the lower-level feeling of SoA. These findings may be explained by and shed light on theoretical frameworks of SoA and stress the importance of the interdisciplinary approach when designing virtual environments.

Chapter 3

Haptics and the gestural agent of automotive interfaces

3.1 Introduction

Gesture recognition technologies provide users control over systems without physical contact with the device (Janczyk et al., 2019). These allow for more flexible and natural interactions (O'hara et al., 2013). One promising area of application is in automotive infotainment systems (Ashley, 2014), with research showing that mid-air interactions with these systems reduce driving errors and improve user experience (Ohn-Bar & Trivedi, 2014; Parada-Loira et al., 2014). However, a concern for mid-air interaction is providing appropriate sensory feedback for the user to perceive system state changes as intended; that is, a crucial factor for their sense of agency (SoA) (Martinez et al., 2017).

These novel interfaces offer systematic manipulation of feedback in response to action, such as visual (Roider & Raab, 2018), audio (Sterkenburg et al., 2017a) and haptic (Shakeri et al., 2018). This offers new ways of manipulating outcome cues, thus shaping retrospective influences on SoA (Moore & Fletcher, 2012; Synofzik et al., 2009; Wegner, 2004). Agency and responsibility are imperative when operating a vehicle and there is recent interest in adapting research methods from psychology to scientifically investigate automotive agency (Cheng et al., 2022; Wen et al., 2019, 2021). However, the focus has typically been on the driving itself and automated intervention. Here, I consider the in-vehicle operation, understanding SoA with gesture recognition and applying this to an automotive context.

In this chapter, first I review the relevant literature by 1) situating the concept of SoA in gesture recognition systems, 2) consider the automotive context as a dual-task and 3) build a rationale for the role of haptics. I will then present two experiments showing how automotive hapticons increase SoA with gesture-based interactions. Finally, I will discuss the findings and implications with the interdisciplinary perspective in mind.

3.2 Gesture recognition and system feedback

Two early theoretical accounts of SoA emphasize either feed forward (Blakemore & Frith, 2003) or retrospective mechanisms (Wegner & Wheatley, 1999). The former being linked to predictive signals arising from internal motor commands and the latter being linked to feedback from the external world. More recent advances suggest an integration of the two (Moore & Fletcher, 2012; Synofzik et al., 2013). In the context of HCI, this means both the user commands and how the system responds can modulate SoA. This notion is exemplified in the *Gulf of execution and evaluation* model (Norman, 1986). The challenge here is that the user carries out their action with the intention to change the system, and in turn the system must respond in a way that the user recognizes as their intended change. This would suggest that input modality and system feedback become important factors. Research supports this, for example showing a diminished SoA for speech input potentially due to competing cognitive resources with working memory (Limerick et al., 2015). Furthermore, that input-latency weakens SoA (Berberian et al., 2013), and even valence of an outcome retrospectively modulates the experience (Wen et al., 2015).

There is a recent uptake in the investigation of SoA with mid-air hand-tracking as a relatively newer mode of input. In terms of input, it appears comparable to physical buttons as research has shown the user's experience of SoA does not significantly differ between the two (Martinez et al., 2017). What is important however, is the feedback received in response. For example, in a virtual environment, mid-air haptics can mitigate negative impacts of latency (Evangelou et al., 2021). Different sensory modalities have also been investigated for responses to mid-air gestures, with mid-air haptics and audio outcome feedback increasing SoA as compared to visual (Martinez et al., 2017). Evidently, gesture input is viable for the user to maintain SoA, however the feedback in response should be taken into consideration.

Notably, the aforementioned research investigated gesture-based input of a button press that emulated the physical action. To allow for more variety in an interaction with more complicated systems, advances in gesture recognition use poses that are performed which are assigned meaning (Jafari & Basu, 2023; Kopinski et al., 2015). For example, they can either be basic such as two or four finger poses, or have some functional value such as opening of the hand to activate a map before manipulating it (Graichen et al., 2019; Graichen & Graichen, 2023). User research in this area is scarce however, and these studies have looked at classic HCI factors such as usability and trust. These novel interfaces use a clear intentional action (gesture) and effect (selection feedback) design, and therefore SoA is a relevant variable.

3.3 Automotive contexts

Recent literature refers to SoA in automotive environments with a focus on automation and driving assistance (Wen et al., 2019). This is due to a close link with ethical and legal concerns of responsibility, particularly as the boundaries of human-machine control are changing. Furthermore, the trade-off between performance and perceived control has been considered. Researchers have investigated how to reduce automated intervention while increasing performance (Wen et al., 2021). Essentially, this is to maintain a user’s SoA while optimizing driving performance. Proposing a shared intention format, their experiment looked at a lane cut-off situation where participants had to decelerate to maintain appropriate inter-vehicle distance. Deceleration was either manual or assisted; assistance was in line with cut-off vehicles and only applied when the participant’s vehicle speed was faster. Results showed faster and smoother deceleration with assisted breaking and no significant impact on SoA. The authors conclude that shared intention of automated driving intervention may work to eliminate the agency-performance trade-off.

What is seldom considered however, is in-vehicle controls in automotive contexts. For example, interacting with UI elements such as infotainment systems and maps. In this sense, driving is often operating at least at a dual-task level, which could be an issue for SoA as research suggests it can decrease under cognitive load (Dewey, 2023) due to requiring a shift in attention (Wen et al., 2019). While driving, then, SoA over in-vehicle commands also becomes important. Research has looked at voice interaction with physical and virtual agents while driving to search for music, change navigation and send text messages (Cheng et al., 2022). They manipulated anthropomorphism levels and found opposing effects for virtual and physical. Perceived control and trust were stronger for high anthropomorphism of a virtual agent, and the opposite for a physical agent; there were no differences in driving performance. Furthermore, perceived control mediated the relationship between anthropomorphism and trust. It seems SoA may be maintained for in-vehicle controls without impacting driving performance.

However, as mentioned above, SoA at the implicit level may be generally diminished when using speech interfaces (Limerick et al., 2015). Additionally, speech activation as a requirement may become tricky when there are other passengers in the car. An alternative consideration is gesture-based interactions. These have been shown to reduce eyes-off-the-road time EORT (Ohn-Bar & Trivedi, 2014; Parada-Loira et al., 2014) and generally perceived as less demanding, more trustworthy and attractive to use (Graichen & Graichen, 2024). However, it remains to be understood how the user's SoA is impacted with gesture-based interactions in the automotive context.

3.4 Automotive agency: the role of mid-air haptic(on)s

A commonly used sensory modality, albeit typically in tandem with touchscreens, is visual feedback. However, visual demands in an automotive context can distract and increase risk of accident (*National Highway Traffic Safety Administration. 2020.* n.d.). Auditory feedback in response to gesture commands has been explored as an alternative to alleviate visual resources (Shakeri et al., 2017; Sterkenburg et al., 2017a; Tabbarah et al., 2023). However, this could compete with other auditory information inherent to automotive contexts, inside and outside the vehicle, so still risks dual task demands and ultimately noisy signals.

In light of these concerns, mid-air haptic technology has been developed which provides tactile information directly to the hand by stimulating the mechanoreceptors via ultrasound waves (Georgiou et al., 2022). This shows promise as an alternative (haptic) modality associated with these interactions, particularly appropriate in automotive scenarios (Georgiou et al., 2022; Harrington et al., 2018; Spakov et al., 2022; Young et al., 2020). This feedback is readily manipulable and can be used to represent the features of selection more closely, without the need to direct visual or audio attention.

With this flexibility, the meaning of the feedback in response to the recognized gesture has also been considered. Brown et al. (2022) look at assigning semantic value via the mid-air haptic medium for the selection of automotive icons to their respective gesture poses. This was intended to enhance not only the user's recognition of a selection, but also the correct selection. Results showed the semantic value of the mid-air haptic patterns were translated and recognized by users, which supported previous work on vibrotactile "Hapticons" (Maclean & Enriquez, 2003). As the recognition of feedback as a cause of our actions is intrinsic to SoA, it can be suggested that this will also benefit from the added recognition value of mid-air haptic meaning.

3.5 Experiment 1

In the current study, we investigate gesture recognition via poses and how differences in the feedback received impacts SoA; namely a) sensory modality of feedback and b) the meaning of feedback. Participants interacted with an automotive themed infotainment menu, selecting one of two icons (fan speed or seat temperature) via a gesture pose and received feedback for their selection. Feedback was either received visually or (mid-air) haptically. Importantly, the feedback meaning also differed such that they were either the same for both icons, arbitrarily different, or semantically different.

To measure implicit SoA, we used the interval estimation paradigm (Engbert et al., 2008). We introduced varying time delays between the gesture and feedback, to which participants would estimate. Differences in the perceived interval between these actions and effects are taken as differences in the magnitude of the experience (Coyle et al., 2012; Evangelou et al., 2021; Winkler et al., 2020). For explicit SoA, we adapted self-report style questions from previous studies (Evangelou et al., 2021) to measure control over actions and feelings of causal influence. We also took measures of trust, usability, technological readiness and computer anxiety to explore associations with SoA.

3.5.1 Method

Study design

A 2 x 3 within-subjects design was used with participants taking part in all 6 conditions (Figure 3.1). There were 2 conditions of sensory feedback: haptic and visual. These were unimodal such that feedback was either given haptically or visually. There were 3 conditions of feedback type: arbitrary same, arbitrary different and semantic. In the arbitrary same condition, the feedback was an upwards scan for either icon selected; in the arbitrary different condition, the feedback was a scan up for selecting the seat icon and a scan down for selecting fan. In the semantic condition, the feedback for the seat scanned in an L-shaped way that represented the seat icon, and the feedback for the fan icon was a circular motion to represent a fan. These hapticons are validated for articulatory directness, identifiability, distinguishability and recognizability in previous research by Brown et al. (2020).

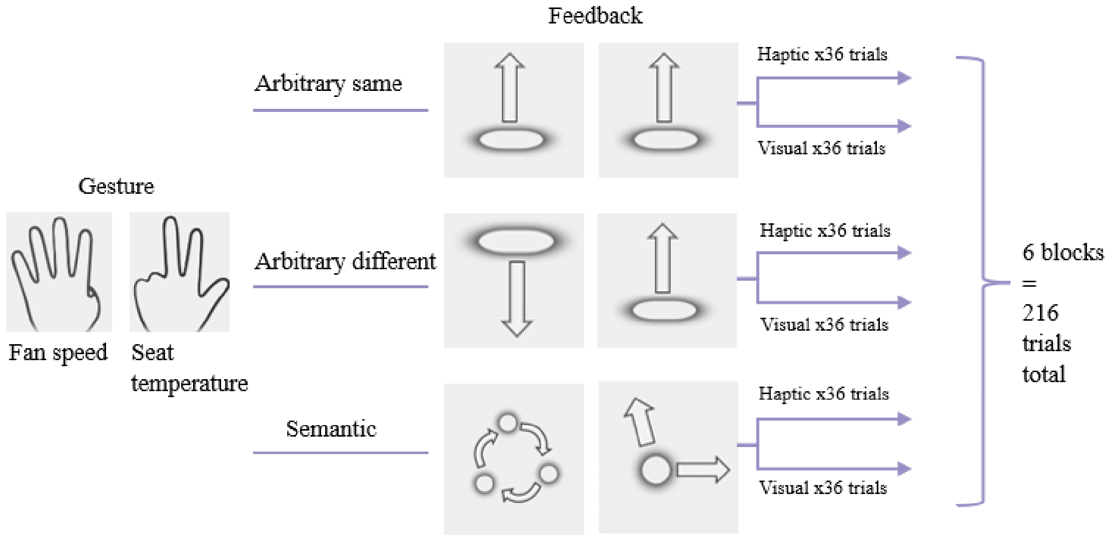

Figure 3.1. *Research design schematic.*

Hypotheses

H1. SoA (explicit and implicit) will be equal to or stronger in the haptic conditions relative to visual.

H2. SoA (explicit and implicit) will be weakest in the arbitrary same condition and strongest in the semantic condition.

H3. The increase in SoA due to feedback meaning (H2) will be more pronounced in the haptic conditions relative to visual.

H4. Greater SoA will be associated with more trust and higher usability in the gesture recognition system.

H5. Greater SoA will be associated with more technological readiness and less computer anxiety

H1 is to establish the overall potential use or even benefits of mid-air haptics for gestural input. H2 is to establish a use for feedback meaning. H3 is to investigate whether adding semantic value to the feedback is particularly beneficial with the haptic modality. H4 is to show a close relationship between SoA, trust and usability with gestural input. H5 was to emphasise the importance of SoA as a variable in HCI contexts.

Participants

G*Power was used to calculated the required sample size of 29 participants for .8 power, based on a previous study (Martinez et al., 2017). 36 participants were recruited via SONA participation database and word of mouth and received £10 compensation. 1 participant was excluded from analysis due to having particular difficulty with selecting the requested icon (error rate ~50% which suggests potentially selecting one of two icons at random). 35 (19 females) were therefore included in the analysis, with ages ranging from 18-52 (*M*=27.4; *SD*=7.6). Participants were screened for handedness, albeit this paradigm was aimed at automotive systems in the United Kingdom, and so was only for use of the left hand, therefore this would only be a potential confound check. There were no reported visual or somatosensory impairments.

Materials and apparatus

A gesture-controlled infotainment system was setup and run via Unity engine (v2020.3.27f1), with a fan speed and seat temperature icon. These icons were selectable via a 4-finger pose and a 3-finger pose, respectively (see Figure 3.1). The interaction was enabled by an Ultraleap STRATOS Explore development kit which consisted of a Leap Motion camera and an ultrasound array. This device reads the gesture pose as appropriate input and provides mid-air haptic feedback as the ultrasound focalises on parts of the hand, stimulating the mechanoreceptors and effectively transmitting tactile sensation (Carter et al., 2013). The haptic sensations used were scan up, down, a circular sensation in correspondence with the fan icon and/or an L-shape in correspondence with the seat icon. Visual animations were also used which matched the haptic sensations.

A 14” HD monitor was used with participants sitting a safe distance from, with an arm rest on the side of their left hand. The Ultraleap device was positioned where the hand is tracked at a height where the arm is slightly upright in a way that would be used in an automotive environment (Figure 3.2). The gesture input was followed by either a visual animation outcome or a haptic sensation, depending on the condition, and 1s later a UI panel opened which was used to input estimates via the keyboard. Headphones were used to minimise the possible conflict between the ultrasound audibility and the mid-air haptic tactility.

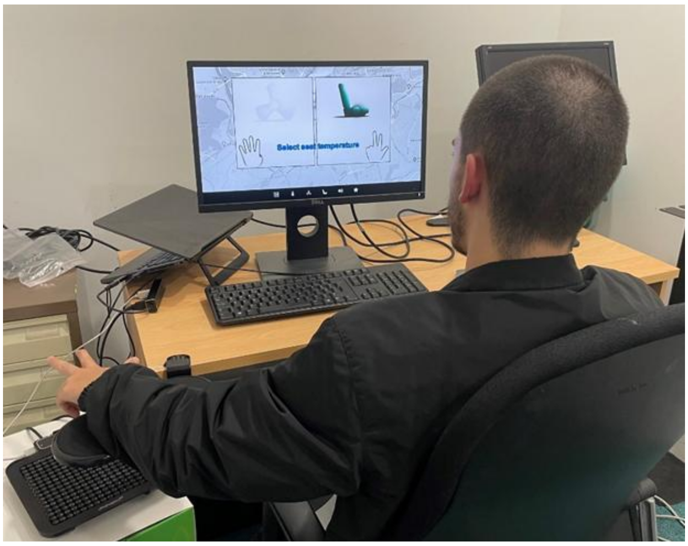

Figure 3.2. *Apparatus and setup*

Tasks and measures

Sense of agency We used the interval estimation method to measure the implicit sense of agency which requires participants to directly estimate the interval between actions and outcomes. Participants would make the gesture pose and receive the (haptic or visual) feedback after a time interval they were told would vary between 1-1000ms. As a standard format

(Engbert et al., 2008), this actually varied pseudorandomly at only 3 different time intervals – 100ms, 400ms or 700ms (Figure 3b). Participants entered their estimates in the UI panel manually after each trial. Shorter interval estimations indicate a greater sense of agency.

Explicit agency was measured using self-report by having participants rate the amount of agency they feel during an interaction. Two questions were adapted from (Evangelou et al., 2021) and tailored to the gesture interaction: "I feel in control when making my gesture command" and "I feel I the feedback is caused by my gesture command". As we included the element of selecting the icon as requested in this paradigm, we also had a rating of responsibility: "I feel responsible for which feature is selected". All ratings were taking on a Likert scale from 1 (strongly disagree) to 7 (strongly agree) and taken every 18 trials (twice per block). Higher ratings there represent greater agency.

Trust and usability HCI measures of trust and usability were adapted to the task-at-hand as a post-hoc measure of user's trust and experience with the gesture control infotainment system. We tailored the Trust Between People and Automation scale (Jian et al., 2000) which then consisted of questions such as "I am suspicious of the gesture control system's intent, actions and outputs" and "The gesture control system is dependable". These are taken on a 1-7 Likert (non-numbered click-and-drag slider) scale and averaged so that scores ranges between 1 (low trust) and 7 (high trust). The short version UEQ-S (Schrepp et al., 2017) was used to measure pragmatic (e.g. inefficient/efficient) and hedonic (e.g. boring/exciting) usability, with each word at opposing ends of a 1-5 non-numbered slider scale.

Individual differences in HCI We measured computer anxiety using the 19-item CARS (Heinssen et al., 1987) which consisted of items such as "I am afraid that if I begin to use computers I will become dependent upon them and lose some of my reasoning skills" and

“Learning to operate computers is like learning any new skill—the more you practice, the better you become”. These are measured on a Likert scale of 1-5, with total summed scores ranging from 19 (low anxiety) to 99 (high anxiety). We also measured technology readiness using the 16-item TRI 2.0 (Parasuraman & Colby, 2015) which consisted of questions such as “Technology gives people more control over their daily lives” and “Sometimes, I think that technology systems are not designed for use by ordinary people”. These were also measured on a 1-5 Likert scale and the total mean score represented this from 1 (low) to 5 (high).

Procedure

Prior to the experimental session, participants completed the CARS and TRI 2.0 online. For the experimental session, participants first underwent a learning phase to adjust them to the apparatus and introduce them to the gesture control infotainment system. During this, both icons were presented on a screen the entire time, including the appropriate gesture poses (Figure 3.3). These gesture poses were also verbally told and physically demonstrated to them.

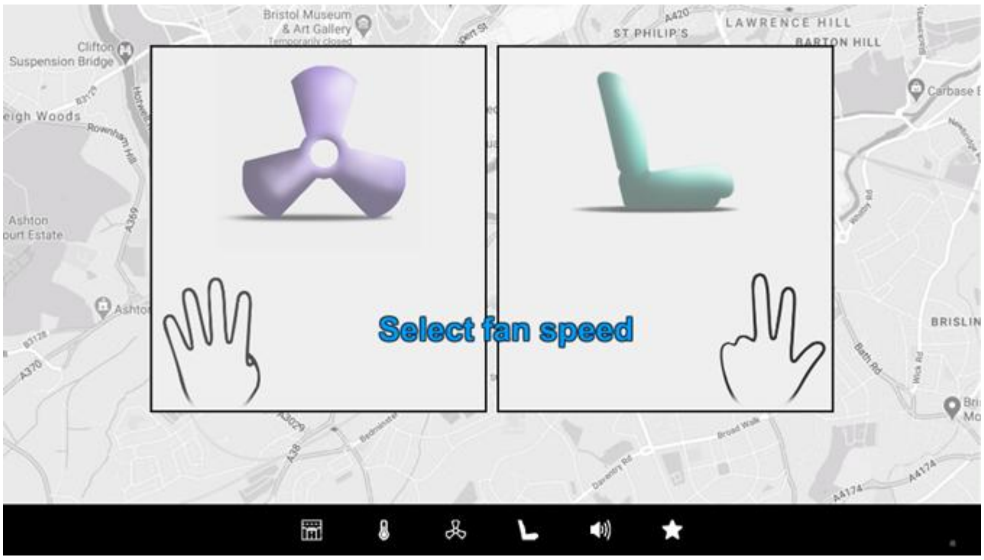

Figure 3.3. *Practice phase screen with poses and icons*

Each gesture pose was followed by both the visual and haptic stimulus simultaneously. There were 10 practice trials which consisted of them selecting the requested icon, with varying time intervals between when they make the gesture and the feedback is given. For this practice phase only, the correct interval was displayed on screen to give them a sense of the millisecond timescale. All participants experienced the same time intervals in the practice phase, these were (in a randomized order; in ms): 50, 200, 400, 600, 800, 950.

For the experimental phase, participants were simply requested to select an icon and were told that intervals would now vary anywhere between 1-1000ms. They were told when each block would consist of either haptic feedback or visual; they were not told of what type of feedback (arbitrary same, different or semantic) this would be. Each feedback type condition was completed for each sensory modality consecutively. For example, in the arbitrary different condition, the haptic block was completed and then the visual block. Conditions were counterbalanced to account for order effects. For context, a typical experimental trial in the semantic visual condition would include: the participant being requested to select an icon (e.g. fan speed), making the required gesture, receiving the feedback after the delay and then enter their estimate (Figure 3.4). There were 6 blocks and 36 trials per block (Figure 3.1). Within these blocks, there were 12 trials of each interval, 18 of each requested icon, and self-reported agency measures taken twice (every 18 trials).

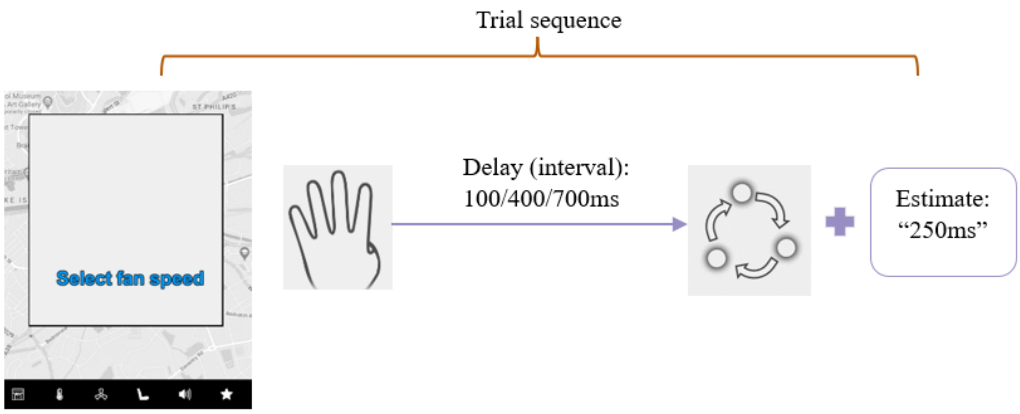

Figure 3.4. *A typical experimental trial sequence. NB intervals were pseudorandom such that each was played 12 times each per block (36 trials) but in a random fashion. They then entered their estimate via the keyboard and pressed enter to start the next trial.*

After the interval estimation task, participants completed the Trust Between People and Automation scale and UEQ-S. This way, the questions were tailored to the gesture control system just used and was reported via a click and drag slider UI. They were then asked if they had any questions or thoughts, and debriefed where requested.

3.5.2 Results

Interval estimations were averaged for each condition so that *lower* scores indicate *greater* implicit agency. Self-reported *control, causation,* and *responsibility* scores were averaged respectively so that *higher* scores indicate *greater* explicit agency. No outliers were detected (all absZ<3). Data were processed in Excel and analyses were carried out in Jamovi 2.

Sensory modality and feedback meaning on interval estimations

A 2 x 3 repeated measures (RM) ANOVA was carried out with sensory modality (haptic or visual) and feedback meaning (arbitrary same, arbitrary different or semantic) on interval estimations (Figure 3.5). There was a significant main effect of sensory modality, $F(1, 34) = 9.16$, $p=.005$, $\eta_p^2 = .21$, such that interval estimations were shorter in the haptic conditions as compared to visual ($M_{difference}=-33.14$). There was no significant effect of feedback type, F(2,

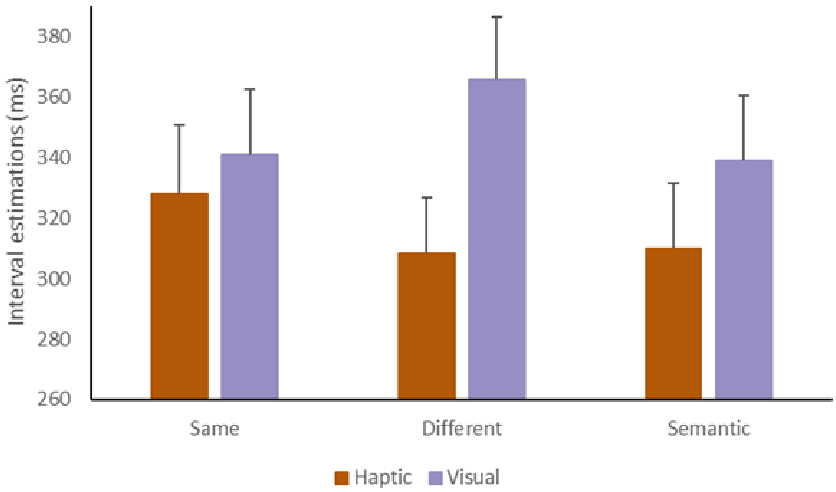

Figure 3.5. *Mean interval estimations by sensory modality, as a function of feedback meaning. Error bars represent standard error across participants.*

68) = 0.25, p=.778, η_p^2 = .01. There was also no significant interaction between sensory modality and feedback type, F(2, 68) = 1.78, p=.176, η_p^2 = .05. Overall, this suggests that implicit SoA was significantly greater with haptic feedback than with visual, and that there was no influence of the meaning of feedback received.

Sensory modality and feedback meaning on self-reported agency

Due to significant departures from normality in the self-report data (Shapiro Wilk, p<.001, Skewness Z>1.96), we applied the aligned rank transform (Wobbrock et al., 2011) before conducting the ANOVAs. This method permits factorial ANOVA on non-parametric data to also examine interactions.

Control A 2 x 3 RM ANOVA was carried out with sensory modality (haptic or visual) and feedback meaning (arbitrary same, arbitrary different or semantic) on the aligned ranks for self-reported control over the gestural input action. There were no significant main effects of sensory modality, F(1, 34) = 0.09, p=.771, η_p^2 = .00, nor feedback meaning, F(2, 68) = 0.43, p=.651, η_p^2 = .01. There was also no significant interaction between sensory modality and feedback meaning, F(2, 68) = 0.36, p=.703, η_p^2 = .01. Overall, this suggests there were no effects of outcome feedback on ratings of control over the gesture action made.

Causation A 2 x 3 RM ANOVA was carried out with sensory modality (haptic or visual) and feedback meaning (arbitrary same, arbitrary different or semantic) on the aligned ranks for self-reported causal influence over the feedback (Figure 3.6). There was a significant main effect of sensory modality, F(1, 34) = 5.02, p=.032, η_p^2 = .13, such that ratings of causal influence over the feedback was greater with haptics as compared to visual ($M_{difference}$=-0.17). There was no significant effect of feedback meaning, F(2, 68) = 0.16, p=.855, η_p^2 = .01. There was also no significant interaction between sensory modality and feedback meaning, $F(2, 68) = 0.42$, p=.656, $\eta_p^2 = .01$. Overall, this suggests that self-reported causal influence was significantly greater with haptic feedback than with visual, and that there was no influence of the meaning of feedback received.

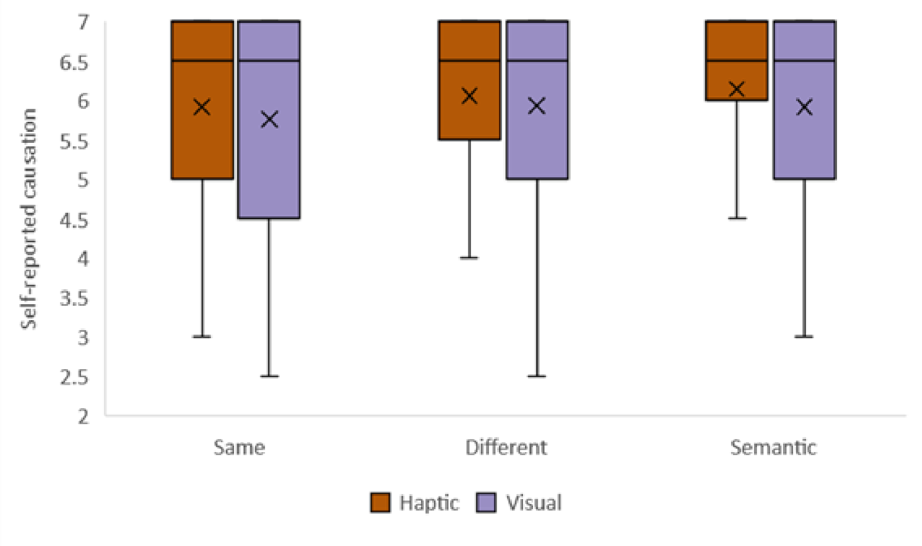

Figure 3.6. *Ratings of causation plotted as a function of sensory modality and feedback meaning. The middle lines of the boxplot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range or minimum or maximum*

Responsibility A 2 x 3 RM ANOVA was carried out with sensory modality (haptic or visual) and feedback meaning (arbitrary same, arbitrary different or semantic) on the aligned ranks for self-reported responsibility for the icon selection. There were no significant main effects of sensory modality, $F(1, 34) = 0.21$, p=.638, $\eta_p^2 = .01$, nor feedback meaning, $F(2, 68) = 0.38$, p=.689, $\eta_p^2 = .01$. There was also no significant interaction between sensory modality and feedback meaning, $F(2, 68) = 0.47$, p=.629, $\eta_p^2 = .01$. Overall, this suggests there were no effects of outcome feedback on ratings of responsibility for which icon was selected.

Relationship between agency and other HCI factors

To explore the relationship between agency and other HCI factors, we looked at correlations between the measures (Figure 3.7). For implicit agency, interval estimations were averaged across conditions. For explicit agency, self-reported control and causation were averaged across conditions. Spearman's correlations were used where there were significant departures from normality.

Implicit agency did not significantly correlate with any of the other HCI factors (all p>.05). Explicit agency significantly positively correlated with trust, $r_s(35) = 0.644$, p<.001, 95% *CI* [0.37, 0.62], and negatively with computer anxiety, $r_s(35) = -0.364$, p=.031, 95% *CI* [-0.36, 0.03], but only showed a marginal positive trend with technological readiness, $r_s(35) = 0.326$, p=.056, 95% *CI* [0.01, 0.61], and usability, $r_s(35) = 0.211$, p=.061, 95% *CI* [0.32, 0.61]. Overall, this suggests there is a relationship between SoA and trust with gestural input, and SoA and general computer anxiety. Additionally, albeit with caution, there is a potential relationship between SoA and perceived usability with gestural input, and SoA and general technological readiness.

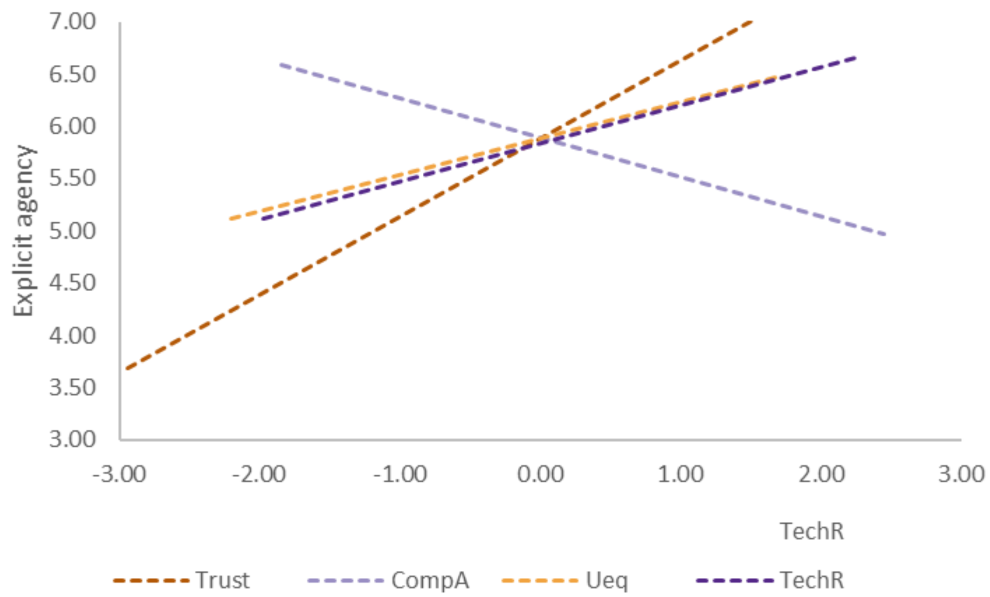

Figure 3.7. *Correlations between explicit agency and HCI factors. All scores on HCI scales standardized for parity on the graph (centered around 0). CompA = Computer Anxiety. Ueq = Usability. TechR = Technological readiness.*

Interim summary

Together, these results show that the haptic modality significantly improves implicit SoA and explicit judgements of causation as compared to visual, independent of whether the feedback is meaningful or not. They also suggest that reporting a greater SoA in the interaction is associated with having more trust in the system; additionally, there is a marginal trend as such with usability. Finally, having more general anxiety around HCI is associated with reporting less SoA; there is also a marginal trend as such with general technological readiness.

3.6 Experiment 2

Experiment 1 did not find any effects of feedback meaning, rather an overall effect of sensory modality. However, this was compared to visual effects and not directly testing it in a dual task driving context. We extend this here to a more ecologically valid context by applying the interval estimation paradigm to the gesture-based automotive infotainment system during a driving simulation exercise. Participants carried out a dual task which required driving around a track in a simulator while selecting the icons using mid-air gestures. We also used a passive control condition often seen in binding studies (Bednark et al., 2015; Cravo et al., 2009), where they would estimate the time between two unrelated tones – this was also while driving. Participants either received mid-air haptic or audio feedback – audio is the typical form of feedback in currently available automotive gesture-control systems (Ohn-Bar & Trivedi, 2014; Stecher et al., 2018). We also measured trust and usability between the conditions and average speed throughout was taken as a measure to account for driving performance/behaviour.

3.6.1 Method

Study design

A repeated measures design was used with all participants taking part in all conditions: haptic, audio and passive (Figure 3.8). The Latin square method was used to ensure a clean counterbalanced design and account for any order effects. With 24 interval estimation trials per block, each interval was presented 8 times in random fashion. For the active blocks, a trial consisted of selecting the requested icon while driving and receiving feedback (haptic/audio) after a short delay and estimating the delay. For the passive block, a trial consisted of listening to two tones with a short delay between them and estimating the delay.

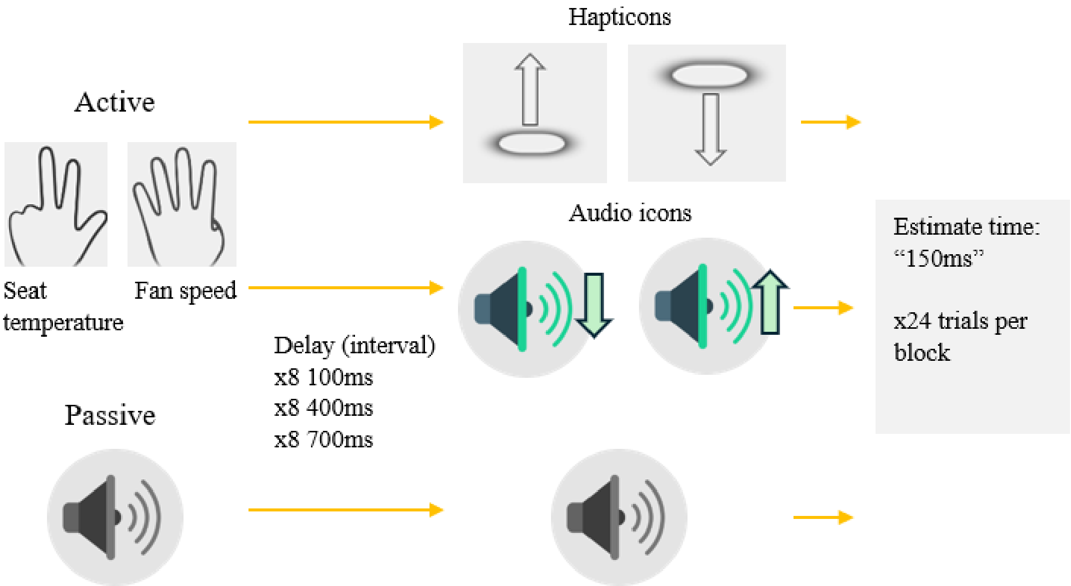

Figure 3.8. *Experimental procedure schematic and trial structure. NB hapticon images representing mid-air haptic scan up and down; audio icons representing high and low pitches; passive involved no active gesture and both tones were a middle pitch dissimilar to the audio icons.*

Hypotheses

H1. Interval estimations will be shorter in the active conditions than in the passive, indicating the presence of SoA.

H2. Interval estimations will be shorter in the haptic condition compared to audio, indicating an increase in SoA.

H3. Self-reported SoA, trust, and usability will be higher in the haptic condition as compared to audio.

H4. Greater SoA will be associated with more technological readiness and less computer anxiety

H1 was to verify SoA in the active conditions and H2 to then compare the magnitude. H3 was to look at explicit agency and explore other HCI factors of the user's experience. H4 was to explore where SoA in this context is associated with individual differences in attitudes toward HCI.

Participants

30 participants (17 female, 2 prefer not to say) were recruited via posters and word of mouth and received £10 compensation. Ages ranged from 19-40 (*M*=27.8; *SD*=4.7). Participants were screened for handedness and driving experience as potentially confounding variables. All participants had normal or corrected-to-normal vision and no reported somatosensory impairments.

Materials and apparatus

The driving simulator setup (Figure 3.9) included a car shell which provided separate in-vehicle sound for the gesture selection task. Separate speakers outside of the vehicle played the in-game sounds and the projector displayed this on an outer screen. BeamNG.drive (v0.29.1) (BeamNG, 2022) was used for the driving simulation, using the time trial mode on the Italy Mixed Circuit map which used mixed terrain including gravel and dirt roads. This version provided 12 checkpoints in the form of red beams of light to give a clear path and allowed data collection of average speed. The vehicle type was automatic, and participants were not required to use a gearstick at all, only two pedals – accelerate and brake – with their right foot. NB holding the brake pedal down when the vehicle is at a stop would put the car in reverse and there were buttons on the steering wheel for mechanics such as rear-view, but this were never used.

An Ultraleap STRATOS Explore development kit was set up inside the vehicle, positioned to track the user's hand when moved left of the steering wheel (Figure 3.9). This device consists of a Leap Motion camera (v5 Gemini SDK) and an ultrasound transducer array, enabling a touchless interaction with gesture recognition and haptic feedback by stimulating the mechanoreceptors on the hand to transmit tactile sensation (Georgiou et al., 2022). An infotainment system interaction was setup in Unity engine (v2020.3.27f1), consisting of a fan speed and seat temperature icon. Gestures required to activate these were a 4-finger pose and 3-finger pose, respectively (Figure 3.8), with a mid-air haptic scan down the hand for fan and up the hand for seat for a duration of 1s. These hand poses and haptic feedback were chosen as they are distinctly different as also discussed in (Young et al., 2020). The audio feedback version was a high pitch tone for fan and a low pitch tone for seat. These also lasted a duration of 1s to ensure consistency with the haptic condition and were played through separate in-vehicle speakers. The gesture recognition was generally accurate and on rare occasions trials where participants felt it inadvertently selected the icon were rendered void (<1% trials).

Figure 3.9. *Driving simulator setup, internal and external.*

Tasks and measures

Driving For the driving task, participants were specifically asked to drive carefully and more realistically rather than race, simply following the checkpoints. They were particularly instructed to avoid crashing/damaging the in-game car to an extent that it alters the driving mechanics. This was due to having to reset the car which meant losing the in-game average speed check data – average speed over the full 2 laps for each respective block. We took this data for exploratory measures however, and to account for any differences in driving behaviour. Any such resets due to crashing did not mean losing any main SoA data with the gesture interaction. We also asked participants how in control they felt with respect to the driving on a Likert scale from 1-7.

Sense of agency To measure implicit SoA, we used an interval estimation paradigm where participants are asked to estimate the time interval between actions and effects (Engbert et al., 2008). To do this, we introduced a time delay between when they make the gesture pose and when they received the feedback, to which they were told varied from 1-1000ms. In reality there were only 3 intervals – 100ms, 400ms, 700ms – which is a standard format to give the perception of complete variation (Moore et al., 2009). As this task was done amidst the driving, participants were required to verbalize their estimate aloud. Shorter time estimates are considered to reflect a stronger experience of agency. We also included a passive control (no agency) condition whereby no gesture actions were made, instead they simply estimated the time interval (same variation) between two tones played through the in-vehicle speakers (different pitch to that of the active condition). Comparisons between active and passive conditions provide further insight into a categorical presence of SoA (Bednark et al., 2015; Cravo et al., 2009).

For the explicit measure of agency, we used a more straightforward self-report style. With respect to control and causation as key factors of SoA (Moore, 2016), we adapted two questions from a previous study (Evangelou et al., 2021) and tailored them to the task by asking: "*How much control did you feel in terms of going to make the gesture action?*" and "*How much do you feel the (haptic/audio) feedback was caused by your gesture command?*". These were asked on a Likert scale of 1-7 and taken once at the end of each block.

User experience For exploratory reasons, we also took other HCI factors via self-report for each condition (haptic and audio). These were: "*How in control did you feel over the driving*?" (driving), "*How much did you trust the gesture recognition system when selecting your icon?*" (trust), "*How efficient did you find the gesture recognition system?*" (efficiency), and "*How innovative did you find the gesture recognition system?*" (innovativeness). This allowed us to examine whether there were any differences in perceived trust and usability between haptic and audio feedback, and whether they felt there were any altering effects on their driving. These were taken on a 1-7 Likert scale.

As a post-hoc measure of general trust and experience with the gesture control infotainment system, we adapted HCI scales to be utilized in context. The Trust Between People and Automation scale (Jian et al., 2000) consisted of questions such as "*The gesture control system behaves in an underhanded manner*" and was measured on a Likert slider scale from 1-7. The UEQ-S (Schrepp et al., 2017) was used to measure both pragmatic (e.g. complicated/easy) and hedonic (e.g. conventional/inventive) usability on a slider scale which ultimately scored from 1-5.

HCI factors For more exploratory factors, we took general measures of computer anxiety and technology readiness. We used the 19-time CARS (Heinssen et al., 1987) which consisted of questions of fear such as "*I hesitate to use a computer for fear of making mistakes that I cannot correct.*", and anticipation such as "*The challenge of learning about computers is exciting*.". This uses a 1-5 Likert scale and totals a score from 19 (low anxiety) to 99 (high anxiety). The 16-item TRI 2.0 (Parasuraman & Colby, 2015) was used which is a streamlined version of technology readiness, consisting of items such as "*In general, I am among the first in my circle of friends to acquire new technology when it appears*." These also use a 1-5 Likert scale, and a final mean score then ranges from 1 (low readiness) to 5 (high readiness).

Procedure

Participants completed the CARS and TRI 2.0 prior to the experimental session. They were told that they will be carrying out a dual-task involving driving in a simulator and using a gesture control system to select in-vehicle features. A practice lap was completed to become familiar with the mechanics and the track. The focus then turned to the interval estimation task, where they completed a practice phase without driving to understand the task. The infotainment screen was presented to them, informing them of the poses and icons, and we physically demonstrated this. 6 practice trials were conducted with both haptic and audio feedback, where they were also received feedback of the exact interval to give a sense of the millisecond timescale. All participants experienced the same 6 intervals in a random order (in milliseconds): 50, 200, 350, 500, 750, 900. Practice trials were also conducted with the passive condition where they would simply estimate the interval between two tones.

For the experimental phase, participants were told that the time intervals would now vary randomly between 1-1000ms. At the start of each block, they were familiarized with the condition (haptic, audio or passive) by starting the drive and running two interval estimation trials. For context, a typical trial in the haptic condition would include: (during the drive) the experimenter requesting the participant to select an icon (e.g. seat temperature), the participant making the required gesture pose (3-finger pose), receiving the haptic feedback (scan up) after a delay (e.g. 400ms), then verbally estimating that delay while continuing to drive. A full block would be completing 2 laps of the course while doing this, with the instructions to select the icon given at each checkpoint to ensure consistency across participants. With respect to avoiding a crash, we informed them that they are entitled to slow down where necessary when doing so. This resulted in 24 interval estimation trials per block (Figure 3.8), and they would answer the self-reported agency, trust and usability questions at the end of each *active* block respectively.

At the end of the experimental tasks, participants completed the Trust Between People and Automation scale and the UEQ-S. This was tailored to the task that they just completed. Finally, they were asked if they had any questions and debriefed on the experiment. The whole session would typically last up to 1.5hrs.

3.6.2 Results

Checks were first carried out whether driving experience or any demographic factors affected SoA. No differences were found in implicit nor explicit agency as per which side of the road participants had driven on before (all $p>.05$), nor any association with driving experience (all $p>.05$). Age and sex were also not influential factors (all $p>.05$). Preliminary checks found no difference in average speed between any of the conditions (Figure 3.10). Additionally, that SoA over the in-vehicle task did was not correlated with average driving speed (all $p>.05$). Together, this suggests both actively using mid-air gestures while driving does not impact average speed and that results discussed below were not confounded by differences in this driving behavior.

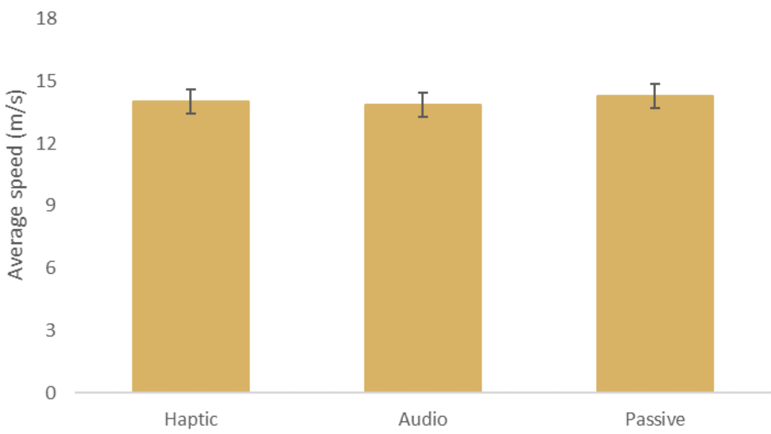

Figure 3.10. *Average speed per condition in meters per second (m/s). Error bars represent standard error across participants.*

Sensory feedback on interval estimations

A repeated measures ANOVA was carried out comparing interval estimations between the haptic, audio and passive conditions (sphericity assumed, Mauchly's W, p = .580). There was a significant effect (Figure 3.11), $F(2, 58) = 13.71$, $p<.001$, $\eta_p^2 = .32$, with interval estimations being shortest in the haptic condition (M=306.3; SE=17.8). Bonferroni corrected paired-comparisons found large significant differences between haptic and audio conditions, $M_{Difference}$ = -81.98, SE = 17.58, $t(29) = -4.66$, $p<.001$, d=-0.85, 95% CIs [-117.9,-46.0], haptic and passive conditions, $M_{Difference}$ = -73.22, SE = 15.5, $t(29) = -4.72$, $p<.001$, d=-0.86, 95% CIs [-104.9,-41.5], but not audio and passive conditions, $M_{Difference}$ = 8.76, SE = 18.37, $t(29) = -0.48$, p = .637, d=-0.09, 95% CIs [-28.8,46.3]. Overall, this shows implicit SoA was much stronger in the haptic condition. Additionally, with comparable effects between audio and passive conditions, this suggests a potentially diminishing implicit SoA in the audio condition.

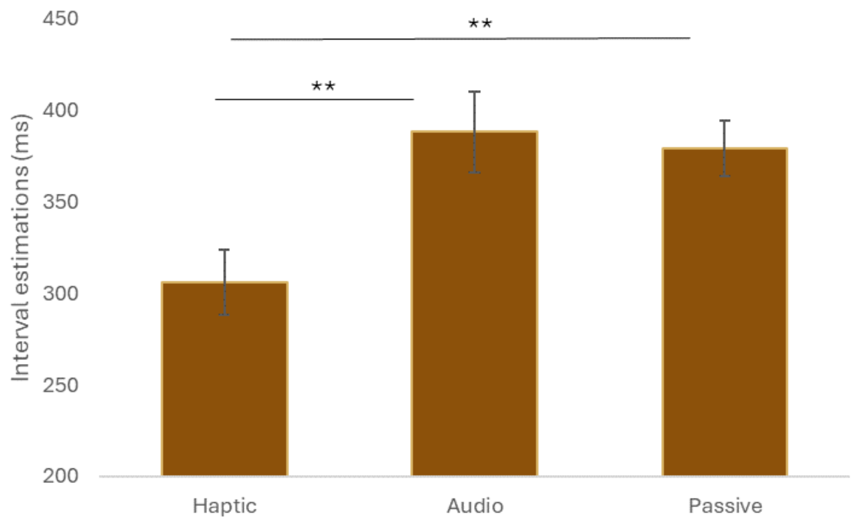

Figure 3.11. *Mean interval estimations in milliseconds (ms) per condition. Lower scores indicate greater agency. Error bars represent standard error across participants. **p<.001*

Sensory feedback on self-reported agency and user experience

Due to significant departures from normality across the self-report measures (Shapiro-Wilk, $p<.05$), non-parametric, Wilcoxon signed-rank tests were used.

There was no significant difference in self-reported control over actions ($W(29) = 91$, $p = .885$) nor causal influence over feedback ($W(29) = 103.5$, $p = .742$) between haptic and audio conditions. There was also no difference in feelings of control over the driving, $W(29) = 67$, $p = .422$. Overall, this shows that explicit judgements of agency for both in-vehicle and driving controls did not differ as a factor of sensory feedback.

There was a significant difference in trust between the haptic and audio conditions (Figure 3.12), W(29) = 134, p = .028, r_b=-0.57, 95% CIs [0.00,1.5], such that participants reported more trust in the system when there was haptic feedback compared to audio. There was however, no significant differences in reported efficiency (W(29) = 107, p = .145) nor innovativeness (W(29) = 81, p = .063), between haptic and audio feedback. Overall, this suggests participants generally find the gesture-based system innovative and efficient but appear to trust the mid-air haptic feedback more.

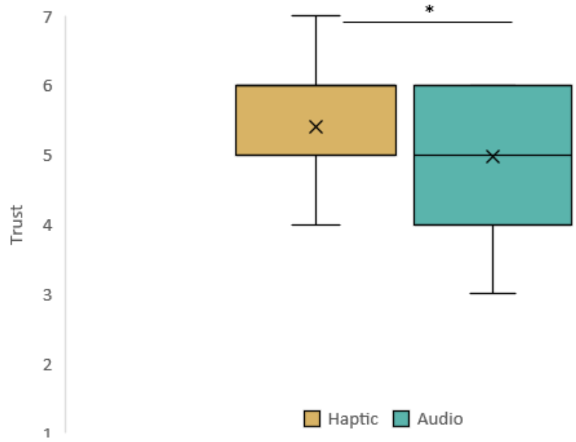

Figure 3.12. *Trust ratings plotted as a function of feedback. The middle lines of the boxplot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range or minimum or maximum. *p<.05*

Relationship between agency and other HCI factors

No significant correlations were found between SoA measures and general trust and usability with the gesture control system (all p>.05). This suggests SoA is a potentially independent psychological factor for the user with gesture-based interactions.

No significant correlations were found between SoA measures and general computer anxiety and technology readiness with HCI (all p>.05). This suggests user SoA with gesture-based interactions may be separate from their general anxiety and familiarity with technology.

Interim summary

Together, these findings suggest that users feel SoA over gesture-based interactions, while driving, with mid-air haptics where they may not with audio. This was picked up at the implicit level specifically and independent of driving experience and average speed. They also had more trust in the system with mid-air haptic feedback. The association between SoA and general trust and usability with the gesture-based system was not replicated here. Finally, the relationships between SoA and general HCI anxiety and readiness were also not replicated here.

3.7 Discussion

These studies sought to investigate the effects of mid-air haptic feedback for a gesture recognition automotive UI system. The findings suggest mid-air haptics generally strengthens SoA compared to visual and audio feedback and remains valid in a typical driving dual task scenario. A relationship between SoA and other HCI factors such as trust and computer anxiety was also partially supported.

Results from Experiment 1 extend previous research by showing stronger SoA with mid-air haptic feedback compared to visual for gesture recognition poses. Martinez et al. (2017) looked at mid-air haptics for touchless interfaces with an in-air button press activation and found it to improve SoA as compared to visual. Here, the gesture is somewhat more separate from the outcome as the pose-feedback model does not emulate a physical interaction as would a button-press typically be accompanied by tactile feedback. Previous research has shown weaker binding for visual outcomes compared to audio in typical button press tasks (Imaizumi & Tanno, 2019; Ruess, Thomaschke, & Kiesel, 2018). Binding is weaker for visual outcomes compared to haptic here, and the case for explicit SoA – judgements of causal influence specifically – as well as implicit. This implicates the importance of sensory feedback for outcomes in an agentic chain, with a crucial role for mid-air haptics in both feeling and judging causality via voluntary actions.

No effect of feedback meaning in Experiment 1 is surprising given the importance of sensory prediction congruency shown in previous research. Lafleur et al. (2020) manipulated this by having the visual result of a pinch action either match the actual force applied or not, which modulated SoA. Here, we manipulated the meaning of the feedback received such that it was either arbitrarily the same or different for each pose, or uniquely represented the icon. The results show the positive impact of mid-air haptics does not depend on this, but also more interestingly and perhaps unexpectedly, that differences in the haptic meaning received did not impact SoA. It may be that these more differences in semantic meaning specifically are more beneficial for recognition of the icon selected and hedonistic qualities (Brown et al., 2022, 2020).

In contrast to previous research, Experiment 2 showed mid-air haptics also strengthened binding compared to audio feedback. In Martinez et al. (2017) study with the in-air button press, they found mid-air haptics and audio to elicit comparable binding. Here, we have combined gesture-based interactions for an infotainment system in a driving simulator for a more ecologically valid dual automotive task. We find that mid-air haptic and audio cues are not comparable here, and mid-air haptic feedback significantly increases SoA where it potentially diminishes for audio feedback – comparable to the passive condition. Previous research suggests that if context requires, bodily signals such as afferent tactile information play a crucial role in determining the source of the perceived sensation (Pyasik et al., 2019, 2021). It is possible that in this context where attention is directed more to a primary task (i.e. driving), mid-air haptic (i.e. tactile) signals directly to the hand play this crucial role. Notably, this difference was not picked up at the explicit level and highlights the importance of utilizing robust methods which capture potentially different components of a complex psychological experience.

Together, this shows that sensory feedback is a relatively influential external cue in an agentic chain, highlighting the importance of retrospective cues with respect to already available prospective cues (Moore & Fletcher, 2012; Synofzik et al., 2013). The prospective cues in this case being the gesture action and feedback received remaining voluntary and consistent. From the HCI, perspective, these retrospective cues can be thought of as in the gulf of evaluation phase in response to user input (Limerick et al., 2014; Norman, 1986). For example, the sensory modality used to display the outcome can affect the way it is interpreted and evaluated by the user with respect to their intentions.

Mid-air interactions for automotive UI are considered to offer several benefits for the user over more commonly used touchscreens. These include removing physical constraints and general usability preferences (Ohn-Bar & Trivedi, 2014; Parada-Loira et al., 2014). Of particular importance though, is the decrease in risk of accident due to reduction in visual and cognitive demands (*National Highway Traffic Safety Administration. 2020. Overview of the National Highway Traffic Safety Administration's Driver Distraction Program.*, n.d.). Research shows these interactions do minimize competing visual information and indeed reduce eyes-off-the-road time (Sterkenburg et al., 2017a). The question then turns to ensuring the user feels SoA over the in-vehicle system. While auditory displays have been shown as viable for the interaction in terms of eyes-free information (Shakeri et al., 2017; Tabbarah et al., 2023), our findings show that they may not be sufficient for the user's SoA. In contrast, mid-air haptic feedback as confirmation for gesture recognition could quite significantly foster user SoA, as well as increase their trust in the system.

This research has provided an exploratory opening into the relationship between trust and agency when using gesture control to operate an automotive UI system. In Experiment 1, we find that the more agency was reported in the interactions, the more they also reported having trust in the system. There was also a trend as such with agency and usability, suggesting a potentially similar relationship. This suggests that the judgements of control and influence you have over a system may be related to the amount of trust you have in it, and how usable you find it. These suggestions are cautionary however, as even those Experiment 2 was under different conditions (i.e. dual task), this was not replicated.

Our exploratory findings also provide insight into the relationship between general anxiety when it comes to engagement with technology and their reported SoA. In Experiment 1, we find that higher general computer anxiety was associated with lower reported agency. There was also a trend as such with technological readiness and agency. This suggests that the more apprehensive around using technology, and potentially also a general lack of propensity for engagement with technology, the less you also judge having control over it. This is interesting and speaks to wider discussed issues around the self and agency in HCI (McCarthy & Wright, 2005), as well as the role of affect (Hudlicka, 2003). For example, future research into improving people's attitudes towards technology and reducing anxiety around this potentially leads to feeling more like an agent in the interactions. Similarly, these suggestions are posed with caution due to not replicating these effects in Experiment 2.

One limitation here pertaining to Experiment 1 is the inclusion of too many – 6 – conditions here which decreases the power when looking at the smaller effects. For example, looking at Figure 5, it appears there are larger differences between haptic and visual conditions when the feedback is assigned at least arbitrary differences. Future research could utilise just 2 more conditions for a more powerful statistical analysis.

Another limitation here is that the passive control condition in Experiment 2 used audio feedback which, although using a different pitch tone, was the same sensory modality as one of the active conditions. As interval estimations in both were comparable, it does leave question whether this is just an effect of sensory modality. Although much previous research would suggest this is not the case (Cravo et al., 2009; Wiesing & Zimmermann, 2024), including using a passive haptic-audio condition (Antusch et al., 2021), a control with a passive haptics condition would ensure this in future research.

Finally, we consider is a lack of extra informative data such as eye tracking and more detailed driving performance in Experiment 2. Previous research suggests gesture-based systems with audio or haptic feedback do reduce eyes-off-the-road time (Shakeri et al., 2018; Tabbarah et al., 2023). Without the use of eye-tracking here however, we are unable to show that here nor further extend this by looking at any relationship with SoA.

In sum, these studies provide novel investigation of SoA with mid-air haptics for gesture-based automotive interactions. We show an overall benefit for mid-air haptic feedback strengthening the user's SoA with gesture recognition systems. This also extends to a driving scenario in comparison with typically used audio feedback. We also suggest, with caution, SoA as an important factor to consider in the wider context of HCI and use of technology. To our knowledge, this was the first application of an implicit measure of SoA in a driving simulator and the results stress the importance of this interdisciplinary approach.

Chapter 4

Haptic reliability and the awareness of intentions

4.1 Introduction

Humans experience the intention to act, which gives rise to the sense that our actions are internally generated (Rigoni et al., 2010). Although these actions may then cause further events and give rise to SoA, the awareness of intention is considered distinct (Haggard, 2008). The elements are similar in that it requires a conscious experience of planning and generating an action; however, a following external event need not be realized. As a subjective experience it is malleable and understanding under what conditions is important as this awareness of intention is a crucial factor for SoA (Gallagher, 2000; Moore, 2016).

Similarly to SoA, there are contrasting perspectives on whether our conscious intention to act is indeed internally generated, a post-hoc inference, or an integration of the two (Schultze-Kraft et al., 2020). Previous research looking at the sensory feedback as a potential external cue for inferring intention typically relied on audio or visual action consequence cues (Banks & Isham, 2009; Matute et al., 2017; Wen et al., 2018). Mid-air haptics offers a way to completely add or remove the touch that so often accompanies action. This poses new ways to investigate awareness of intention and contribute to contrasting theories on prospective and retrospective mechanisms. Furthermore, this could inform HCI of whether haptics plays a more fundamental role for user intention.

In this chapter, I first review the relevant literature and build rationale by 1) introducing the concept of the will and the awareness of intention, 2) gaining insight from schizophrenia and 3) considering the role of mid-air haptics. I will then present two experiments supporting a more predictive mechanism for formulating intentions and discuss the findings.

4.2 The will (W): when and how?

Volition refers to our capacity to generate and perform actions, and we tend to experience some recognition of our intention – or not – to act (Haggard, 2019). This is central to notions of freedom and responsibility and is therefore socially and psychologically significant.

Despite the importance of intention, it was, historically, neglected in psychology. This was due, in part, to difficulties studying it empirically. An influential study by Libet et al. (1983) helped address this problem by introducing a paradigm that enabled intention to be quantified. Participants observe a rotating clock while making simple yet spontaneous movements of the wrist. They were asked to report the time they felt the conscious will to act. This will to act (termed 'W') appeared to be on average ~200ms before the act itself. Libet also took electroencephalography (EEG) recordings during the movement to measure the readiness potential, a build-up of neural activity that reliably precedes the onset of a voluntary action. It was found that the RP not only preceded the action itself, but also W by ≥300ms. This implies that an action is already being initiated before participants are aware of willing that action. Although the findings of Libet et al. have proved controversial, the Libet clock method is seen as a viable method of scientifically investigating the awareness of intention and action (Haggard, 2005).

The conscious experience of our intentions being the sole driver of our movements is so compelling, yet evidence on the processes associated with W suggests a more complicated picture. One notion supporting W being tied to internal motor processes is the lateralised RP (LRP). LRP is the contralateral activity beyond that of the more general RP, thought to be more closely tied to the preparation of movement (Eimer, 1998). Haggard and Eimer (1999) extended this by investigating its relation to W. They median split participants' W by earlier and later judgements and analysed the differences in RPs and LRPs. LRPs were found to occur earlier on early awareness trials and later on later awareness trials; this was not the case for RPs. It would appear then, that LRPs do covary with W judgements and the authors concluded that LRP reflect and internal process that leads to awareness of movement initiation.

However, it is not clear whether W reflects an internal process only, as there may also be post-hoc factors. For example, Choudhury and Blakemore (2006) refer to motor correction studies that demonstrate our intentions of correcting our movements become apparent after the actual correction of movement, suggesting that the conscious experience of will may be a post-hoc inference. One way to test this, is through manipulating sensory feedback for voluntary actions we make. Banks and Isham (2009) carried out a Libet clock study and manipulated the timing of auditory feedback in response to participants' actions, delaying it between 5-60ms. They found that W was drawn toward the delay in a linear fashion such that the longer the delay, the later the W. They also modified this with visual feedback of either instant (0ms) or delayed (120ms) and found a shift in W toward the delayed visual feedback. The authors suggest W is a postdiction based on available cues, and thus the timing of the conscious decision to act is inferred rather than perceived.

Rigoni et al. (2010) extended this by examining event-related potentials (ERP) in relation to such delayed auditory feedback and W. They found the action-effect negativity (N_{AE}) component, regarded as a system that detects expectancy violations was sensitive to 250-300ms auditory delays. Furthermore, it was found that these changes in N_{AE} were associated with the changes in W. It was concluded that the inference of conscious intention is influenced by a system that monitors actions by comparing the predicted and actual consequences. Such an action-monitoring system should be influenced by the reliability of feedback. Indeed, the reliability of audio tone action consequences has been shown to modulate RPs (Wen et al., 2018) such that they are larger for predictable vs. unpredictable outcomes.

These post-hoc inferences based on incoming sensory data are echoed in Friston's (2010) "free energy" principle whereby the brain aims to minimise surprise through predictive processing. These unexpected sensory consequences – a form of prediction error – referred to as surprise are thought to include those events contingent on our own actions. Following this, Edwards et al. (2012) state "In the case of a prediction error arising from the comparison of precise sensory data and a relatively imprecise prior belief, the mean of the posterior will be closer to the mean of the sensory data.". In this way there is room for post-hoc influences on W judgements, and that influence is dependent on the relative precision of both internal motor processes and sensory feedback. This is confirmed in research showing that W is shifted toward delayed sensory feedback (Banks & Isham, 2009; Rigoni et al., 2010). What is not known however, is whether W is affected by the uncertainty of receiving any sensory feedback more generally.

4.3 Insights from schizophrenia

A prime example of a disorder demonstrating abnormal experiences of volition is schizophrenia (Richardson et al., 2020). Symptoms include delusions of control which refers to the belief of an external force as the cause their seemingly voluntary action. For example, a patient might be aware it is their body part moving but state that they do not experience this happening under their will (Mellor, 1970). It has been suggested that these symptoms are in-part due to a lack of awareness of their intentions, such that intentional actions are formulated but are not brought to conscious awareness (Frith & Done, 1989). Indeed, recent research has shown that W is not reported significantly before M in patients as it typically is with control subjects (Richardson et al., 2020). Furthermore, a study by Moore and Bravin (2015) showed that higher schizotypal traits in the typical population are associated more variable awareness of intention, as indicated by standard deviation of W judgements. These studies confirm the existence of intention awareness deficits in schizophrenia (or high schizotypy).

Importantly, it follows that this deficit in awareness of intention would augment prediction errors – if awareness of intentions is compromised, then the ensuing actions and effects will be more surprising. A consequence of this is that W judgements should be particularly prone to capture by incoming sensory data, and indeed, research has suggested that volitional experience in schizophrenia patients is over-reliant on sensory feedback (Haggard, 2017). We will examine this more formally in the current study by manipulating the predictability of sensory (haptic) feedback. We will assess the influence of this feedback in these different conditions on W judgements and explore whether the magnitude of this effect increases as a function of schizotypal severity.

4.4 Haptic reliability

The aforementioned research looking at sensory feedback typically posed audio cues as a consequence of the performed action. Mid-air haptics, however, stimulates the mechanoreceptors to provide touch sensation directly to the hand (Carter et al., 2013; Georgiou et al., 2022). In this way, it can be considered more intimately tied to the action itself as opposed to being a consequence of the action. For example, previous research has shown that proprioceptive and haptic feedback improves performance in brain-computer interfaces (BCI) compared to visual feedback shown on a screen (Cantillo-Negrete et al., 2019; Gomez-Rodriguez et al., 2011; Ramos-Murguialday et al., 2012; Vukelić & Gharabaghi, 2015). This is illustrated by increasing motor cortex activity and facilitating motor imagery when participants can see and feel the movement in synchrony with their intention via the robot hand/arm. Thus, there appears to be something additional about the perception of touch and proprioception together; that is, haptic perception (Hannaford & Okamura, 2016). However, the effects of haptics on the awareness of intention, as such W, has not been directly investigated.

Overall, existing research indicates both predictive and postdictive effects on intentions. We utilise mid-air haptics to formally address this by examining the effect of haptic reliability during action on W judgements. If W is based exclusively on preparatory motor signals, incoming sensory data should not influence it. On the other hand, if it is based exclusively on external sensory feedback, then it will be entirely dependent on incoming sensory data. However, if it is an integration of the two, W would be influenced by incoming sensory data *only* when it is unreliable.

4.5 Experiment 1

In light of the above, we manipulate the presence and absence of touch sensation associated with a button-press action via mid-air haptics. We manipulated the presence of this feedback as well as its predictability, such that the presence or absence of this feedback was predictable (100% present or absent) or it was unpredictable (50%). Using the Libet clock method, we had participants report their W and M judgements for these conditions. We also measured schizotypal traits using the Cardiff Anomalous Perception Scale (CAPS: Bell et al., 2006) and Peters Delusion Inventory (PDI: Peters et al., 2004). We predicted that W would be impacted by haptic feedback particularly in the unpredictable conditions. That is, W will be delayed in the unpredictable condition only on the trials where haptic feedback is present compared to no-haptic trials and the predictable conditions. We also expected to see a relationship between schizotypal traits and the effect of feedback predictability on W judgements. That is, a negative relationship between schizotypy and W such that higher schizotypal trait scores are associated with more delayed W, and that this is more pronounced in the unpredictable conditions.

4.5.1 Method

Participants

Previous research found a *d* of .58 for the effect of action consequence reliability and RPs (Wen et al., 2018). For a desired power of .9, we calculated the required sample size to be 34 using G*Power (Faul et al., 2007). For full counterbalancing, we recruited 36 participants (28 females, 2 non-binary and 1 prefer not to say) in total via the SONA participation database and email. They either received course credits or £10. Ages ranged from 18-42 (*M*=23.4; *SD*=5.9). All participants were right-handed and there were no reported visual or hearing impairments.

Materials and apparatus

A Libet clock (Figure 4.1) adapted from Libet et al. (1983) was setup and run via Unity game engine (v2019.4.12f1). This consisted of a virtual clock on the screen with 60 evenly spaced lines around the edge, numbered in increments of five. There is one clock hand that spins around at 2.56s (2560ms) per full turn. An Ultraleap STRATOS Xplore development kit (Figure 4.2) was used for reading when participants made the (virtual) button press, consisting of a leap motion hand-tracking camera and an ultrasound array which provided the mid-air haptic feedback by transmitting tactile sensation directly to the hand (Carter et al., 2013). The mid-air haptics used here was a 200ms burst of haptic feedback during the button press movement.

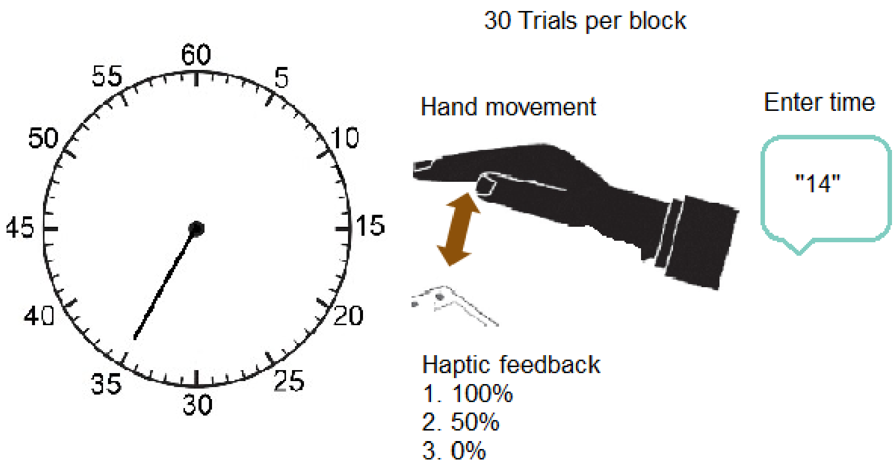

Figure 4.1. *Experimental trial structure and conditions.*

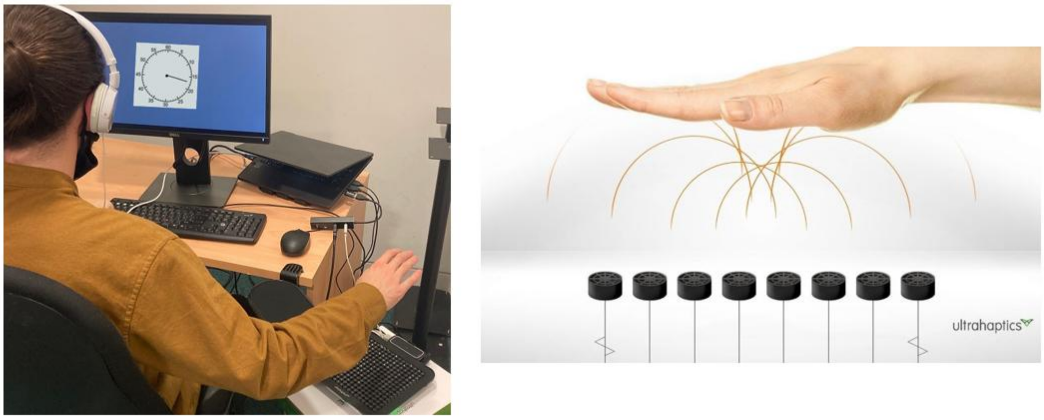

Figure 4.2. *The experimental setup. The interface scene of the hand and button. The Ultraleap apparatus providing hand-tracking and mid-air haptics.*

A 14” HD monitor was used to display the Libet clock with participants sitting at a safe distance. The Ultraleap device was placed where the hand could be tracked at a height where the button-press feels natural, and an arm rest was provided to keep their arm from getting tired and ensure consistency (Figure 4.2). The hand-tracking camera registered the button press motion as complete at 1cm depth. Following this, the clock hand continued rotating for a random time between 1500-2500ms before going to the self-report screen. This UI screen allowed participants to report their time estimations with their other hand and press enter to begin the next trial. Mild, non-intrusive brown noise was played over headphones to mask auditory output created by the ultrasound speakers (used to deliver haptic feedback).

Tasks and measures

For the M judgements, participants to were told to report the time they actually completed the button press. This was compared to the actual times as a measure of changes in action perception. For W judgements, participants were told to report the time they first felt the urge to act; this was also compared to the actual time they pressed the button as a measure of changes in their awareness of intention.

Two measures of schizotypal traits were taken: CAPS (Bell et al., 2006) which consisted of questions such as “Do you ever hear noises or sounds when there is nothing about to explain them?”, and PDI (Peters et al., 2004) which consisted of questions such as “Do your thoughts ever feel alien to you in some way?”. Both of which, participants could answer yes or no to. When answering yes, three further ratings of distress, frequency and intrusiveness on a scale of 1-5 are taken. Scores are summed and higher scores represent higher schizotypal traits.

Design and procedure

Participants completed the self-report scales before the experiment session. In the experiment session, they were told they would be making simple actions with their hand and providing time estimates related to those actions. They were shown the apparatus and demonstrated the button press action they would be making. When sat down, they were adjusted to the Ultraleap array to ensure it was tracking their hand, reading their button press action and that they could feel the haptic feedback. They were told they are free to make the action at any time of their choosing– not to pre-plan the action in advance. They had 5 practice trials of M judgements and W judgements before beginning the experiment.

For the experimental phase, they were told that during these blocks, they might receive haptic feedback or receive nothing at all, but still need to make the M or W time judgements relating to their button press action. Owing to an occasional technical issue with the hand-tracking device, the time entry screen would appear in the absence of movement. If this happened we asked participants to enter 0 (which flagged it as a false trial), which resulted in ~1% of trials not yielding data.

We used a repeated measures design with three conditions of haptic feedback (Figure 4.1): 100% (predictably present), 50% (unpredictably present/absent), 0% (predictably absent). M and W judgements were made for all three conditions. All participants completed all conditions, with either M or W judgements first – a Latin square method was used to counterbalance blocks within each judgement set across participants. An "End of block" message was displayed at the end of each block; participants were permitted a two minute break in between judgement sets if necessary.

When the session finished, participants were debriefed and asked if they had any questions or if they noticed anything about the experiment.

4.5.2 Results

Both W and M judgements are taken from the actual time of action (estimate-minus-actual), with negative values representing perceived time as before the action and positive values representing after the action (Table 1.1). On average, W preceded M ($M_{Difference}$=-246.5; SE=39.5, p<.001) as proof of concept. For W, two univariate outliers (±3SD) were removed. For M, one univariate outlier (±3SD) was removed.

Table 1.1 *Mean judgements (ms) for each condition with standard deviations in parentheses*

	Predictable		Unpredictable	
	Hap	**No Hap**	**Hap**	**No Hap**
W	-259.6 (197.5)	-259.1 (138.6)	-204.2 (194.9)	-229.2 (198.1)
M	26.6 (189.4)	-13.9 (191.0)	17.8 (203.3)	12.9 (194.6)

Predictability of feedback and W judgements

For the analysis, the randomised block (50% haptic, 50% without) was split by feedback. A 2x2 repeated measures ANOVA was then carried out on W judgements with haptic feedback (with or without) and predictability (predictable or unpredictable) as factors (Figure 4.3). There was no main effect of haptic feedback, $F(1, 33) = 0.64$, p=.431, $\eta_p^2 = .02$. There was a significant main effect of predictability, $F(1, 33) = 6.33$, p=.017, $\eta_p^2 = .16$, such that W judgements were earlier when feedback was predictable compared to when it was unpredictable

($M_{Difference}$=-42.6; SE=16.9, $t(33) = -2.52$, $p = .017$, d=-0.43, 95% CIs [-77.1, -8.11]). There was no significant interaction between feedback and predictability $F(1, 33) = 0.56$, p=.458, η_p^2 = .02.

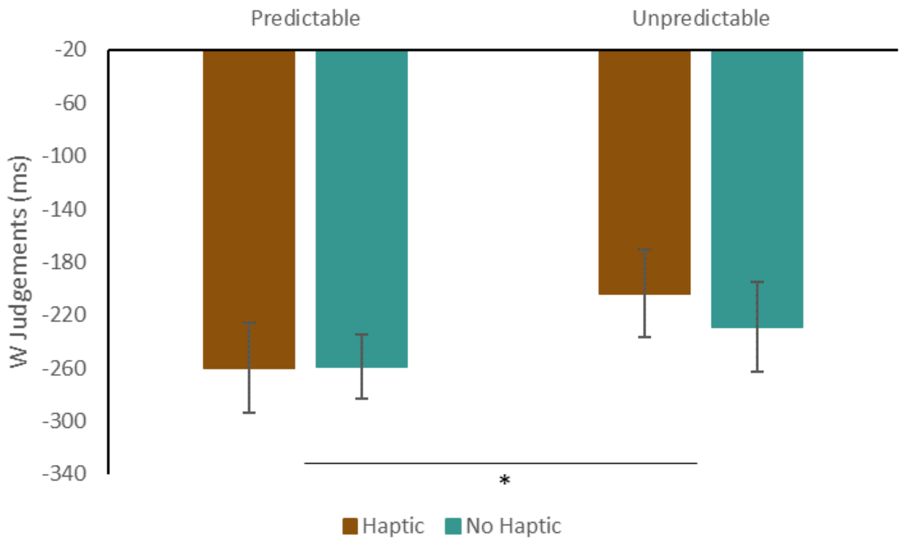

Figure 4.3. *W judgements by feedback, at each level of predictability. The error bars show SE across participants. * p<.05*

A 2x2 repeated measures ANOVA was carried out on W SDs with haptic feedback (with or without) and predictability (predictable or unpredictable) as factors. There were no significant effects (all p>.05), suggesting there was no effect of feedback nor predictability on the variability of W judgements.

Predictability of feedback and M judgements

Due to departure from normality (Shapiro Wilk, p<.001) we used non-parametric Friedman repeated measures ANOVA tests. Effect sizes (Kendall's W value) were calculated as follows (Morse, 1999):

$$W = \frac{\chi 2}{N(\mathrm{p}-1)}$$

where χ^2 is the test statistic, N is the total sample size and $p - 1$ is the degrees of freedom. Holm-Bonferroni corrections were applied to post-hoc tests. Values after the first non-significant result are not reported.

There was a significant effect of feedback on M judgements (Figure 4.4), $\chi^2(3) = 9.41$, $p<.024$, $W = .09$. Post-hoc tests revealed a significant difference ($p=.004$) only between predictable haptic feedback (M=26.6; SD=187.8) and predictable no haptic feedback (M=-13.9; SD=193.9). However, it should be noted that no M judgements significantly differed from 0 (all $p>.05$).

There was no significant effect of feedback on M SD, $\chi^2(3) = 1.56$, $p<.668$.

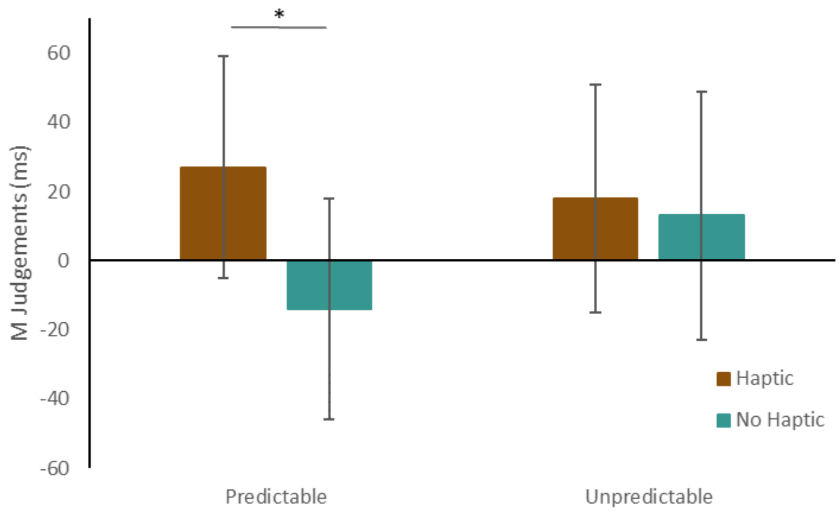

Figure 4.4. *M judgements by feedback, at each level of predictability. Zero represents the actual time of action. The error bars show SE across participants. * p<.05*

Schizotypy and predictability of feedback

Descriptive statistics for schizotypy scores can be found in table 1.2. To examine the relationship between schizotypal traits, awareness of action and intention, and predictability of feedback, CAPS and PDI_21 scores were regressed onto W their variability (Standard deviations of W) in each condition respectively.

Table 1.2 Descriptive statistics for the Peter's Delusion Inventory (PDI_21) and Cardiff Anomalous Perception Scale (CAPS).

	PDI_21	**CAPS**
Mean	77.76	89.65
Standard deviation	48.57	59.65
Range	0-170	0-196
Skewness (SE)	0.185 (.40)	0.278 (.40)
Kurtosis (SE)	-1.019 (.79)	-0.894 (.79)

Surprisingly, neither CAPS (Figure 4.5) nor PDI_21 (Figure 4.6) significantly predicted W and their SDs in any of the conditions (all *p*>.05; Table 1.3). Therefore, we cannot conclude a relationship between these measures of schizotypal traits and awareness of intentions.

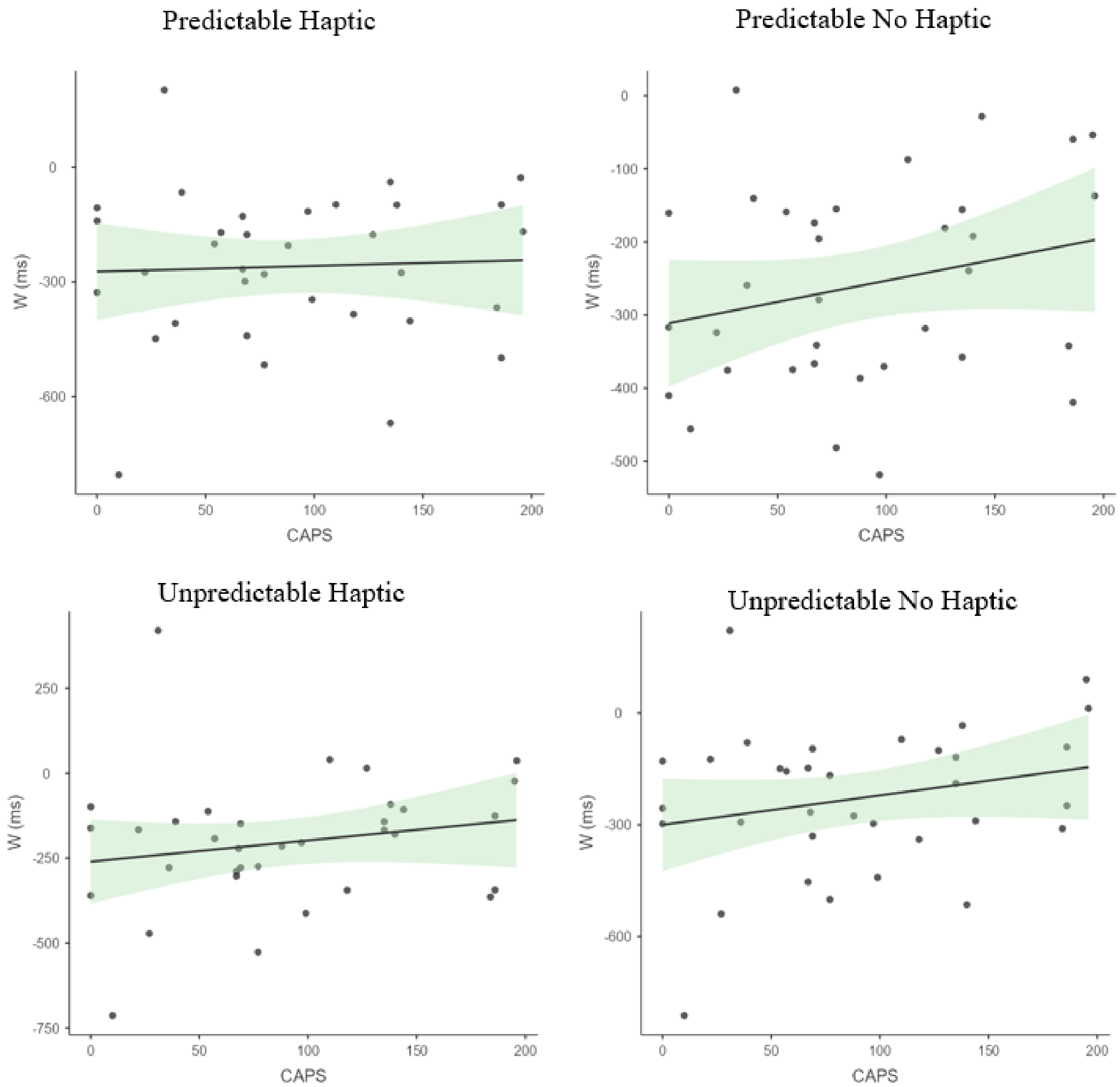

Figure 4.5. *Regression slopes (N =33) for W judgements as a function of CAPS (Cardiff Anomalous Perception) scores in each condition respectively. Positive slopes suggest later W judgements as propensity for schizotypal experiences increases. Shaded areas indicate error bars.*

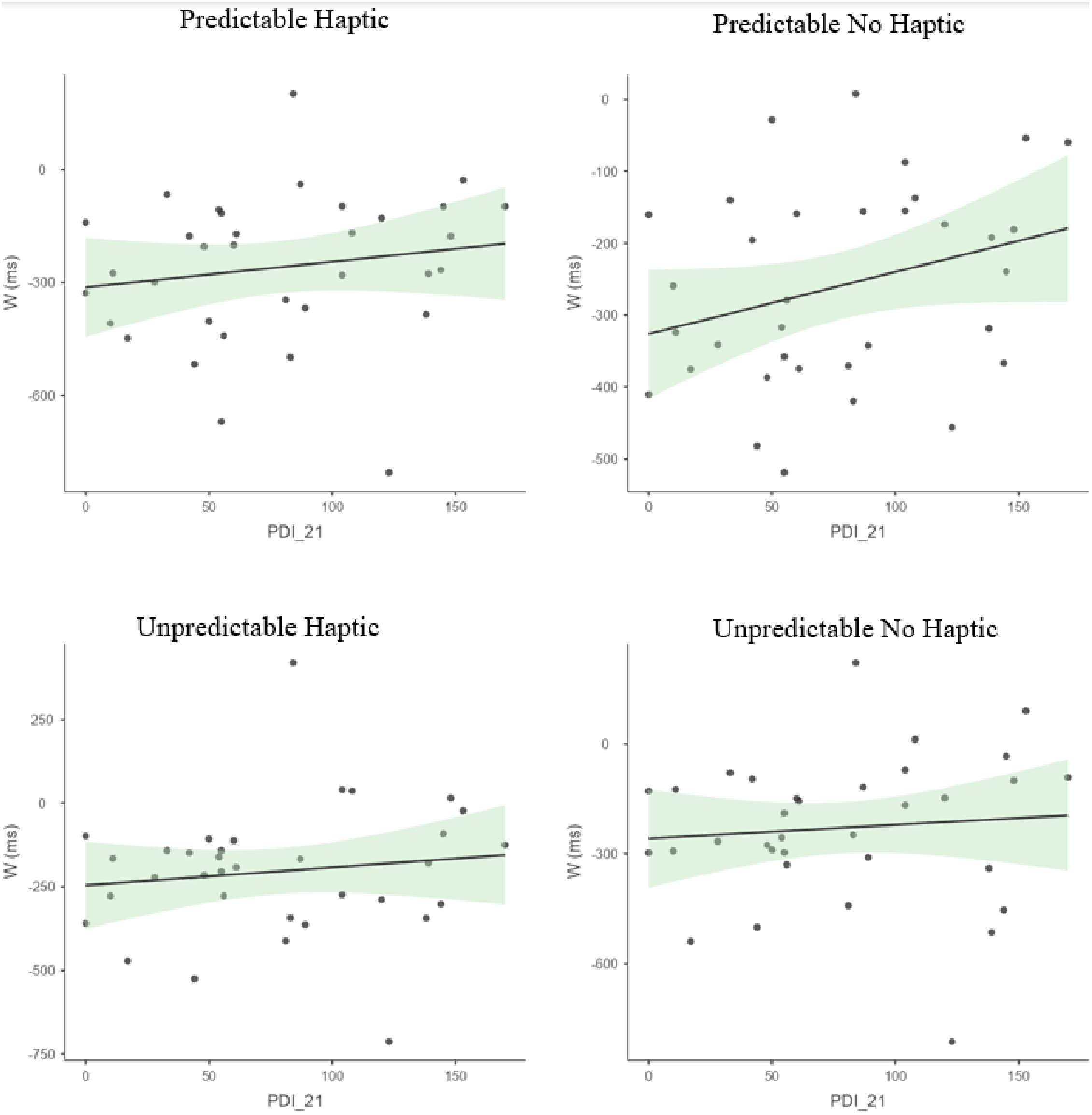

Figure 4.6 *Regression slopes (N =33) for W judgements as a function of PDI_21 (Peter's Delusion Inventory) scores in each condition respectively. Positive slopes suggest later W judgements as propensity for schizotypal experiences increases. Shaded areas indicate error bars.*

Interim summary

Together, these results show that W is delayed overall in the unpredictable relative to the predictable condition, independently of whether there is haptic feedback or not. However, the association between W judgements and schizotypal traits was not significant. Finally, although M judgements significantly differed between conditions, they were generally accurate in their timing.

These findings generally suggest that the ability to anticipate actions is compromised when feedback becomes unpredictable, thus delaying the onset of W. What is not clear however, is whether the delay in W is genuinely linked to reliability; that is, it could simply be due to the presence of uncertainty (50/50). This is something we address in Experiment 2.

Table 1.3 *Simple linear regression results for Peter's Delusion Inventory (PDI_21) and Cardiff Anomalous Perception Scale (CAPS) on W judgements and their variability (W SD) in each condition respectively.*

		PDI			CAPS		
		β	**95% CI**	***p***	***β***	**95% CI**	***p***
W							
Predictable	**Haptic**	0.17	-0.19, 0.52	.341	0.05	-0.31, 0.41	.798
	No Haptic	0.30	-0.04, 0.65	.082	0.25	-0.09, 0.59	.154
Unpredictable	**Haptic**	0.13	-0.22, 0.49	.456	0.19	-0.16, 0.54	.278
	No Haptic	0.09	-0.27, 0.45	.605	0.24	-0.11, 0.59	.176
W SD							
Predictable	**Hap**	-0.09	-0.27, 0.44	.621	-0.02	-0.38, 0.34	.911
	No Hap	-0.27	-0.07, 0.61	.120	0.07	-0.29, 0.43	.679
Unpredictable	**Hap**	0.12	-0.24, 0.47	.512	0.14	-0.21, 0.50	.416
	No Hap	0.21	-0.14, 0.56	.410	0.13	-0.22, 0.49	.450

4.6 Experiment 2

To examine whether W is merely delayed when feedback is unpredictable or if it is instead modulated as a function of its reliability, we manipulated the probability of haptic feedback at 3 levels (100%, 75% and 25%). If reliability is key, then W should be delayed in a linear fashion as probability decreases.

4.6.1 Method

36 participants (25 female) were recruited in total via the SONA participation database and email. They either received course credits or £10. Ages ranged from 18-53 (*M*=27.9; *SD*=7.1).

4 participants were left-handed and the apparatus was setup for the left hand to accommodate this. There were no reported visual or hearing impairments.

The apparatus and procedure was the same as Experiment 1 except we also took a measure of subjective intensity to account for individual differences. During a practice phase becoming accustomed to the apparatus, we asked participants to rate the intensity of the haptic feedback on a scale of 1-7. We had three haptic feedback blocks of 30 trials: 100%, 75% and 25% (Figure 4.6). Participants completed all conditions, the order of which was counterbalanced using the Latin square method was. An "End of block" message was displayed at the end of each block. Participants were permitted a two-minute break in between blocks if necessary.

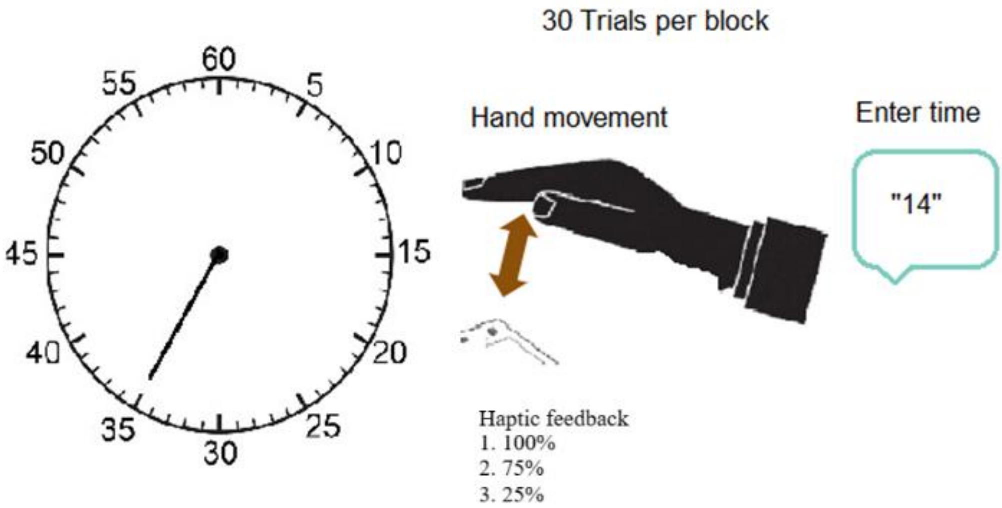

Figure 4.4. *Experimental trial structure and conditions.*

4.6.2 Results

On average, W preceded M again ($M_{Difference}$=-187.5; SE=55.5, p<.001). W was also similar here (M=-234.4; SD=190.6) to Experiment 1 (M=-238.0; SD=164.3) as an indication of consistency. There were no significant correlations between W and haptic intensity rating (all p>.05) showing any differences in reported times were due to individual differences in haptic perception. Finally, no outliers were detected.

Probability of feedback and W judgements

A repeated measures ANOVA was carried out with probability of haptic feedback (100%, 75% and 25%) on W judgements (sphericity met, Mauchly's W, p = .627). There was a significant effect of probability on W judgements, $F(2, 70) = 3.40$, $p = .039$, $\eta_p^2 = .09$. Within-subjects contrasts showed a significant linear trend, $F(1, 35) = 5.91$, $p = .020$, $\eta_p^2 = .14$, such that W was later when the probability of receiving haptic feedback was lower (Figure 4.8). Differences were further examined using 100% as the reference level. There was no significant delay when probability dropped to 75%, $M_{Difference} = -41.91$, SE = 23.04, $t(35) = 1.82$, $p = .077$, d=-0.30, 95% CIs [-88.6, 4.9]); there was a significant delay when the probability dropped to 25%, $M_{Difference} = -54.39$, SE = 22.38, $t(35) = 2.43$, $p = .020$, d=-0.41, 95% CIs [-99.4, -8.9]). A

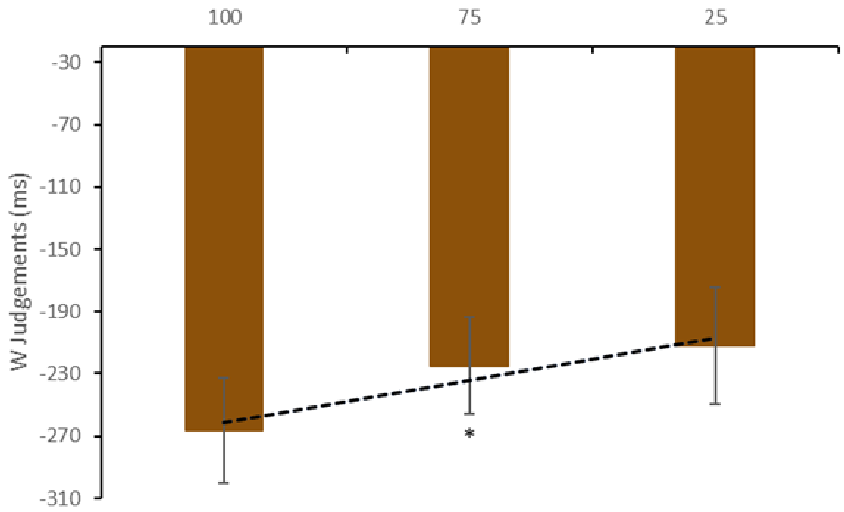

Figure 4.5. *W judgements by probability of receiving haptic feedback. The error bars show SE across participants. Dashed line indicates the linear trend contrast analysis. * p<.05*

repeated measures ANOVA was carried out with probability of haptic feedback (100%, 75% and 25%) on W SDs (sphericity violated, Mauchly's W, p = .005, therefore a Greenhose Geisser correction applied). Although there appeared to be a marginal increase in SDs as probability decreased (Figure 4.9), this effect was non-significant, $F(1.6, 55.1) = 2.71$, $p = .088$ (linear trend, $p = .061$).

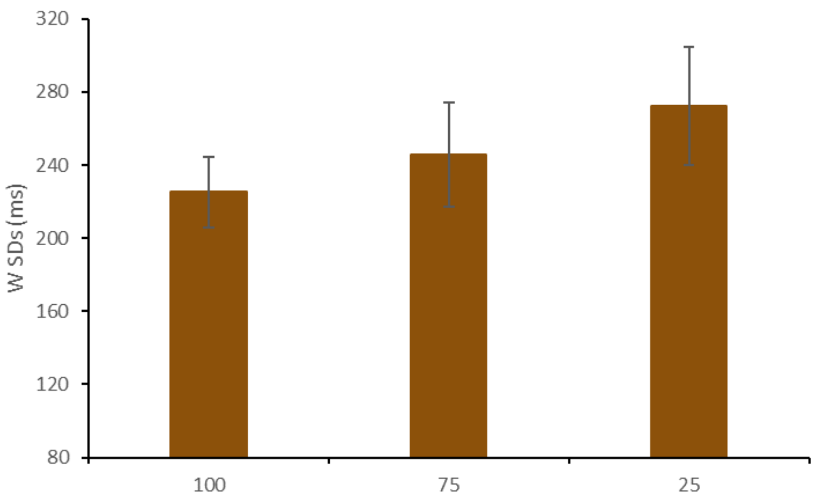

Figure 4.6. *Standard deviations (variability in) W judgements by probability of receiving haptic feedback. The error bars show SE across participants.*

Probability of feedback and M judgements

Non-parametric Friedman repeated measures ANOVA tests were used on M judgements due to non-normal distributions.

There were no significant effects of probability on M judgements, $\chi^2(2) = 2.17$, p=.338, nor their SDs, $\chi^2(2) = 0.39$, p=.823.

Schizotypy and probability of feedback

Descriptive statistics for schizotypy scores can be found in table 1.4. To examine the relationship between schizotypal traits, awareness of action and intention, and predictability of feedback, CAPS and PDI_21 scores were regressed onto W judgements and their variability (Standard deviations of W) in each condition respectively.

Table 1.4 *Descriptive statistics for the Peter's Delusion Inventory (PDI_21) and Cardiff Anomalous Perception Scale (CAPS).*

	PDI_21	**CAPS**
Mean	50.22	57.44
Standard deviation	37.91	51.77
Range	0-169	0-205
Skewness (SE)	1.417 (.39)	1.08 (.39)
Kurtosis (SE)	2.581 (.77)	0.531 (.77)

Similarly to Experiment 1, CAPS nor PDI_21 significantly predicted W and their SDs in any of the conditions (all p>.05; Table 1.5).

Table 1.5 *Simple linear regression results for Peter's Delusion Inventory (PDI_21) and Cardiff Anomalous Perception Scale (CAPS) against W judgements and their variability (W SD) in each condition respectively. 100%, 75% and 25% = Probability of receiving haptic feedback.*

		PDI			CAPS		
		β	**95% CI**	***p***	***β***	**95% CI**	***p***
W							
	100%	0.18	-0.88, 2.77	.300	0.07	-1.64, 1.07	.675
	75%	0.16	-0.88, 2.47	.341	0.09	-1.55, 0.93	.615
	25%	0.15	-1.13, 2.98	.368	0.09	-1.93, 1.11	.585
W SD							
	100%	-0.02	-1.11, 1.00	.915	-0.18	-1.17, 0.35	.283
	75%	-0.01	-1.62, 1.54	.960	-0.16	-1.68, 0.61	.346
	25%	-0.07	-2.16, 1.39	.667	-0.24	-2.17, 0.37	.159

Interim summary

These findings show that W is influenced by the *probability* of receiving haptic feedback; with lower probabilities associated with later W judgements. This suggests that the timing of our will to act is in part based on the reliability of receiving sensory feedback.

4.7 Discussion

The aim of these studies was to investigate whether W is influenced by the reliability of receiving feedback for the action itself and explore a relationship with schizotypy. We find that not only does randomising whether haptic feedback will accompany actions delay W, but that W is delayed as a function of the probability. Notably, this delay was not only apparent when feedback occurred, it was present across trials. These findings contribute to our understanding of the neurocognitive basis of intention by supporting a more anticipatory mechanism for volition. However, no relationship between this and schizotypy was established.

First, results from Experiment 1 indicate a general delayed conscious awareness of intention when sensory feedback is unpredictable. Previous research has shown that we infer the timing of our intentions based on incoming sensory information such that it covaries with the delay in feedback received (Banks & Isham, 2009). Furthermore, that inference of conscious intention is influenced by a system that monitors actions by comparing the predicted and actual consequences (Rigoni et al., 2010). Here, the reported time of intention was modulated by the predictability of feedback for actions, albeit not drawn specifically to sensory (haptic) information. This suggests that while monitoring feedback can update the system in a post-hoc fashion, the intention to act may reflect a more preparatory signal.

Experiment 2 extends this by revealing the reported time of intention to delay in a linear fashion as the probability of receiving haptic feedback decreases. Postdictive accounts suggest that W judgements are inferred from response-based evidence (Banks & Isham, 2010), whereas predictive accounts suggest that W judgements reflect internal preparatory motor signals (Haggard & Eimer, 1999). Here, we propose a predictive account whereby W reflects motor preparation, which itself is informed by feedback expectancy. As such, the more we can predict action-related feedback, the earlier we can formulate our intention to act. This is cautionary given the limited scope of the current experiment, and future research should examine whether this is reflected in RPs to provide converging evidence for this anticipatory account.

Despite no relationship shown with schizotypal traits, our findings may shed light on volitional disturbances in the clinical population. It has been shown that W judgements are significantly delayed in patients with schizophrenia (Richardson et al., 2020). At present it is not clear what is driving this change. Here we propose that our findings may offer an explanation; namely, that it is linked to predictive deficits in patients with schizophrenia. In other words, the reason why the experience of intention is delayed is because patients with schizophrenia are less certain about the sensory feedback pertaining to their actions. This would be consistent with well-established predictive deficits in schizophrenia (Haggard, 2008; Voss et al., 2010). Future research addressing this may be beneficial to HCI applications, as virtual reality with haptic feedback is being explored as a tool for psychotherapy (Vargas et al., 2022).

One limitation here was the lack of a 0% (certain no) feedback condition in Experiment 2. This decision was taken to not risk participant fatigue by having too many blocks and was also informed by there being no interaction/main effect of feedback in Experiment 1. While this did intend to follow up more precisely on the predictability effect found in the first experiment, an inclusion of this condition could offer further insight. Future research could remove the M judgement conditions to give room for including more conditions of W, for example, comparing just 5 conditions: 100%, 75%, 50%, 25% and 0%.

Another limitation concerns the potential confound of intraindividual variability in the haptic perception throughout. While haptic intensity did not show a relationship with any of the measures here, it is possible that participants did not always feel the haptic feedback to a consistent intensity as the session went on. Future research could look at measuring the perceived intensity of the haptic stimulus on a trial-by-trial basis. Furthermore, this could be included even on trials where no haptic feedback was received as previous research has shown comparable anticipatory effects between imagined and actual sensory feedback reflected in RPs (Pinheiro et al., 2020).

In sum, the findings presented here show that being unable to predict sensory feedback related to your action delays onset of intention awareness. With caution, they also indicate the delay increases as the potential to receive haptic feedback decreases. This suggests that the timing of intention is not merely a post-hoc inference. Rather, the formulation of intentions may be underpinned by an anticipatory process informed by expectation of action-related feedback. Furthermore, these findings may shed light on the disruption of intentionality in disorders of volition, something that could be fruitfully explored in future research.

Chapter 5

General discussion

The objective of this thesis was to investigate the role of haptic feedback in modulating the sense of agency (SoA). This was underpinned by an interdisciplinary approach as mid-air haptics was developed to remedy the lack of tactile feedback during touchless human-computer interaction. However, systematic investigation was scarce. Therefore, utilising this newly manipulable feedback to understand SoA and applying psychological research methods to HCI was the principle behind the objective. In this final chapter, I will summarise the findings and discuss their implications, then acknowledge limitations of the research and suggest future directions before concluding.

5.1 Summary of chapters and findings

Chapter 2 situated the agent in the context of virtual reality (VR), taking into consideration that these interactions are not bound by physical laws, which could impact the bodily self. The concept of the virtual self was introduced and the importance of sensorimotor contingencies, thus posing a role for haptics. Two studies were carried out looking at integrating haptics when using virtual objects to carry out actions that cause effects. Experiment 1 showed that the general addition of haptics can improve explicit SoA but does not protect against the negative impact of visual incongruence. Experiment 2 revealed that differences in haptic feedback, potentially due to incongruence, can actually decrease implicit SoA for the user. Notably, these findings also exemplified differences in the feeling and judgement of agency, and a general lack of binding in the implicit measure.

In Chapter 3, the agent was placed in the automotive context where control and responsibility are imperative to vehicle operation. While agency over the driving itself is typically considered, the seldom considered in-vehicle operation was investigated. This is due to recent advances in gesture recognition technology, where the role for haptics is to provide viable feedback in response to the user's commands. Experiment 1 compared mid-air haptic to visual outcomes and manipulated feedback meaning within sensory modalities. Results found an overall increase in SoA with mid-air haptics irrespective of feedback meaning. Experiment 2 extends to an ecologically valid scenario, using gesture control during a driving simulator task, comparing mid-air haptics to typically used audio feedback. Results provided evidence for a large improvement with mid-air haptics, where SoA may even diminish with audio. Explorative factors reveal an increase in trust with mid-air haptics, and tentative relationships between SoA and other important HCI factors such as usability, trust, computer anxiety and technological readiness.

The agent was brought back to a more fundamental yet distinct aspect in Chapter 4; the experience of intention. The influential Libet method and the concept of the will (W) was introduced, and literature reviewed on opposing theories of preparatory versus retrospective inference. A potentially integrative perspective was considered where post-hoc cue effects may depend on expectancy effects, and insight gained from schizophrenia patients being particularly prone. The role for haptics in this case was to test these accounts by manipulating the reliability. Experiment 1 found unpredictable feedback delayed the reported time of intention onset in general, not only on trials with feedback present. Experiment 2 revealed that these delays in intention judgements may increase as the probability of receiving haptic feedback decreases. Despite no relationship found with schizotypal traits, these findings support a predictive mechanism which may reflect volitional disturbances seen in schizophrenia.

5.2 Psychological implications

Below I will discuss what the findings throughout the thesis mean and how they may contribute to our psychological understanding of SoA. Nonetheless, it should be stressed that these are tentative speculations given the limited scope of the current investigation.

5.2.1 Feedback for actions

In a unified, comprehensive model of SoA put together by Legaspi et al. (2019), the action itself is typically seen simply as a mediator between the intention/action selection and the outcome (see Figure 1.5). By utilising mid-air haptics to manipulate feedback related to the action itself in VR (Chapter 2), the effects suggest that how the action is perceived is a relevant cue for the agent. For example, this could be seen as an afferent somatosensory cue for whether the action was executed as planned.

Additionally, affordances in the classic comparator model (Blakemore et al., 2002) are seen as separate with no real influence on the prospective SoA (see Figure 1.3). Affordance refers to the perceived functionality of an object and this informs the range of action possibilities (Gaver, 1991; Kaptelinin & Nardi, 2012; Norman, 2013). Previous research has shown that different interaction techniques can modulate embodiment via shifts in attention to the task (Alzayat et al., 2019), and even induced illusory tool use can influence the mapping of action-related body parts (Garbarini et al., 2015). It is possible here that the effects of these virtual object manipulations are an affordance cue, potentially informing action selection.

5.2.2 Sensory outcomes

A wide variety of retrospective cues which inform the agent have been covered in previous research. These include social cues such as eye gaze (Stephenson et al., 2018) and emotional expression (Barlas, 2019), and contextual cues such as reward (Nataraj et al., 2020) and goal achievement (Kumar & Srinivasan, 2013). Sensory consequences of an action were initially simply part of the intentional binding method to measure SoA (Haggard et al., 2002), however research has shown these to also be a retrospective cue. For example, additional primes Moore et al., 2009), sensory-related arousal (Wen et al., 2015) and congruence of these sensory outcomes (Barlas & Kopp, 2018) can influence.

Findings from Chapter 3 in this thesis show that the sensory modality in which the outcome information is received is a crucial factor. Previous research has examined differences between visual (colour change) and audio (tone) outcomes of a button press (Imaizumi & Tanno, 2019; Ruess, Thomaschke, & Kiesel, 2018). However, research looking at mid-air haptics (Martinez et al., 2017) did not quite separate the outcome from the action. In their experiment, the outcome was a visual or mid-air haptic representation of button press itself and so may have been seen as the action rather than the consequence. In Chapter 3, the feedback in response to the gesture action is a particularly separate consequence, and repeatedly shows strengthened SoA with mid-air haptics. Furthermore, that these differences may even be exacerbated when attention is divided under cognitive load. Previous research has indeed shown that using one's own skin as an input device for an action increases SoA (Bergstrom-Lehtovirta et al., 2018; Coyle et al., 2012). Here, we show that receiving causal outcome information via the skin also does. Thus, sensory information directly to skin receptors may be a powerful cue for informing the agent both that they were the author of the action and the cause of the consequence.

5.2.3 Intention as per anticipation

Literature suggests that the volitional deficit in schizophrenia is due a their intentions not reaching conscious awareness (Frith & Done, 1989). Indeed, research has demonstrated a general delay in when they report their intentions compared the typical population (Richardson et al., 2020). A first experiment in Chapter 4 found a general delayed awareness of intention in the typical population when the potential to receive haptic feedback becomes unpredictable. This may reflect the disruption to intention in schizophrenia and supports a predictive mechanism. A second experiment extended this by showing the awareness of intention becomes more delayed as reliability of receiving feedback decreases. This suggests the more reliable our predictions the earlier we can prepare our actions.

Notably, these disruptions to awareness of intention were not caused *only* when the feedback was perceived. This may shed light on the mechanism underpinning sensory attenuation – a marker of SoA. The classic inhibitory hypothesis states the incoming signal is simply attenuated due to correct prediction (Blakemore et al., 1998). However, a recent preactivation hypothesis suggests the incoming signal is reduced due to comparison to increased activity which already represents the expected stimulus (Roussel et al., 2013). In other words, a preparatory signal to which the incoming stimulus is compared to as expected. Indeed, research supports this showing expected sensory representations from self-produced actions are sharpened (Yon et al., 2018) as opposed to weakened. Furthermore, evidence suggests these predictive signals are unique to voluntary action as they are not present when externally produced effects are temporally predictable (Klaffehn et al., 2019). In Chapter 4, W was impacted by the reliability or potential to receive feedback rather than the feedback itself, reflecting an anticipatory signal and supporting the preactivation hypothesis.

5.3 Implications for human-computer interaction

In this section I will briefly discuss how the findings on the role of haptic feedback may apply to HCI. As above, they remain tentative implications due to the finite experimental scope of this thesis.

5.3.1 The virtual agent

Virtual reality (VR) is just that, virtual, meaning these environments are programmable and therefore permit interactions not readily available or even possible in the real world. This is useful for providing scenarios which serve training (Pantelidis, 2010), rehabilitation (Adamovich et al., 2009) or even entertainment (Hwang et al., 2017) purposes. However, the mapping of both the user's movement commands and how objects respond when interacted with is required (Seinfeld et al., 2020). This means that even though mid-air haptics provides promise in including touch sensation to more naturalised bare hand interactions, it also requires mapping (Young et al., 2020). A first study from Chapter 2 does suggest that the addition of mid-air haptics to virtual object interactions can be beneficial, potentially due to the saliency in comparison to none. However, a second study suggests caution with visual-haptic integration as SoA can be negatively impacted, particularly if not in congruence with each other and emulating physical properties.

Additionally, although explicit judgements of SoA were generally supported in Chapter 2, there is generally a weaker implicit feeling of SoA compared to that captured with physical interactions. This may be because although this is a virtual world which serves purposes mentioned above, the virtual self needs to feel more closely contingent on their real-world self in terms of bodily action representation. It may be that VR has some way to go in providing the user with this implicit feeling that it is their body and their actions, for example with emerging physics-based hand models (Oberweger et al., 2018).

5.3.2 Gesture recognition

Gesture-based systems are being explored in automotive contexts to keep visual attention on the road when interacting with in-vehicle infotainment (Sterkenburg et al., 2017b). However, in such a dual task, the system must provide feedback for the user to be aware their commands are registered and therefore feel SoA. While audio feedback in response to the gesture made is typically used in current interfaces (Shakeri et al., 2017; Sterkenburg et al., 2017a; Tabbarah et al., 2023), it is not ideal as other streams of auditory information remain important when driving. Findings from Chapter 3 suggest that such audio feedback may also be insufficient in providing the user SoA while driving. Where mid-air haptics provides the user with feedback more direct and less noisy in terms of interference, the results also revealed this significantly fostered their SoA. Thus, empirical evidence via scientific rigour suggests mid-air haptics is a viable mode for gesture-based automotive infotainment.

The implications may extend beyond just that in automotive environments. For example, gesture-based interactions are used in other instances of HCI such as distance learning/tele-teaching and enabling HCI for young children (Kaushik & Jain, 2014), and human-robot interaction (Neto et al., 2019). Using mid-air haptics to alleviate the auditory and visual streams for distance learning/tele-teaching would be beneficial to get the most out of the interaction. With young children, sensory feedback is key at this stage of development (Grubb & Thompson, 2004) and so the loss of touch sensation could be crucial; something mid-air haptics could remedy. Finally, interactions with robots can be ambiguous, leading to facets such as human-likeness and intentionality perception influencing the user's SoA (Roselli et al., 2022; Z. Barlas, 2019). Mid-air haptic cues could foster SoA in these joint interactions by providing human-like touch information and also serving as a further confirmation of intentionality cue.

5.3.3 Haptics one can rely on

Providing touch sensation in a contactless interaction involves an array of ultrasound transducers programmed to stimulate focal points on the skin (Hoshi et al., 2010; Takayuki Hoshi et al., 2009). Additionally, to cross the perceptible threshold for human skin, additional techniques such as amplitude modulation (Long et al., 2014) or spatiotemporal modulation

(Frier et al., 2018) are required. Rendering haptics is complex and involves many degrees of freedom, and a particular challenge for *mid-air* haptics i.e. in stimulating the full palmar region of the hand (John et al., 2024). This technology is still developing and as of yet may not always provide the most consistent sensations, whether differing in intensity or even at times not being perceived at all. Findings from Chapter 4 suggest that our experience of intention may depend slightly on how well we can map the expected sensory feedback we will receive when we carry out actions. Implications of this would mean the reliability and consistency of the haptic sensations are an important consideration for optimising our experience of intentional actions and ensuing SoA.

The increasing scope of use for touchless technology bears weight to these implications mentioned. For example, particularly due to the covid-19 era, contactless HCI could become more pervasive, including essential public services such as elevators, ATMs (cashpoints) and pedestrian crossings (Pearson et al., 2022). Reliable and consistent mid-air haptics accompanying these interactions would be crucial in these interactions, as it is imperative that civilians feel a sense of control and responsibility in these situations.

5.4 Limitations and future directions

One general limitation of the work within this thesis concerns the methodology and measurement. Some literature questions the validity of intentional binding as a measure of agency as opposed to integration of two related sensory events (Kirsch et al., 2019; Majchrowicz & Wierzchoń, 2018; Schwarz et al., 2019; Tonn et al., 2021). One study in particular arguing for simply multisensory causal binding finds it in the absence of intentional action (Suzuki et al., 2019). Their study used a VR paradigm with three button press-tone conditions: action, observed fake hand (recordings from respective participants movements) matching for visual, tactile and audio feedback, and observed no hand. Results found lower binding in the no hand condition but no difference between action and fake hand conditions, suggesting that intentional action is not necessary. It is however, not in the complete absence of intentionality, as in the fake hand condition, not only did they observe the action, but they also essentially observed their own action. Considering they also matched sensory information, they satisfied all principles of apparent mental causation, rendering it entirely plausible that illusory SoA was experienced – as empirical evidence has suggested (Cai et al., 2024). Furthermore, rigorous replication has also failed to provide the same result (Wiesing & Zimmermann, 2024). That being said, different cues affecting binding are a valid argument, to which a meta-analysis by (Tanaka et al., 2019) suggests predictability of the timing and identity of stimulus are key. While we did account of temporal predictability by randomising intervals, we did not control for stimulus identity. Future research could include conditions which render (sensory) identity unpredictable i.e. haptic and other randomised within the same block.

Naturally, there is also the general limitation of applying rigorous psychological method to HCI where we only really analysed one part of the user's interaction – initial simple action and effect. HCI is complex and can involve a chain of sequences. For example, in gesture control we select the icon but then also need to manipulate it (Kopinski et al., 2015; Parada-Loira et al., 2014; Tabbarah et al., 2023; Young et al., 2020) i.e. after selecting the fan, use pinch and drag gestures to turn it up/down. Future research could therefore extend the current scope of this thesis by focusing on another part of the agentic chain in HCI.

Additionally, particularly with hand-tracking, we first carry out our action with our physical body which then translates into the action on the system. As such, it is possible that within HCI our actions so-to-speak could even be seen as initial outcomes to our implicit agency processing system. For example, the button press in VR may have been seen technically as an outcome, rendering the following tone a second outcome. Research has shown that binding is significantly weakened for a second effect (Ruess et al., 2018) and this confound could explain the generally weakened binding seen in Chapter 2.

Finally, a promising future direction for SoA research, including that with mid-air haptics, would be to place experiments within overarching frameworks that embed theories of SoA. Wider predictive processing frameworks such as active inference and learning theory (Friston et al., 2016) suggest we build optimal models of the world by learning statistical relationships between actions and events through explorative behaviour. As these probabilistic relationships become detected, it permits exploitative, goal-directed behaviour. This kind of framework embeds the theories of SoA; whether the comparator model or apparent mental causation theory, predicting oneself to be the agent of an event remains at the core. Experiments on action contingency (James W. Moore, Lagnado, et al., 2009) were designed in this manner which led to cue integration approaches, and recent experiments on SoA have explicitly referenced an active inference framework (Wen & Haggard, 2020). The manipulability of mid-air haptics could be utilised to examine SoA within wider aspects of predictive processing. For example, different types of uncertainty have been suggested in previous computational research: expected, estimation and unexpected (Bland & Schaefer, 2012). These refer to inherent probabilistic properties, imperfect response-outcome information, and volatile environments, respectively. Mid-air haptics can be manipulated to give more/less accurate information or, similarly to the manipulations made in Chapter 4 experiments, give more/less expected information. Carefully cultivated experimental designs could utilise this to investigate how different types of uncertainty may affect SoA.

5.5 Concluding remarks

SoA is a fluid experience unifying a complex series of events including intention, action and effects. Throughout this thesis, haptic feedback has been shown to modulate the psychological experience at each stage of the process. As an action cue, its impact depends on the integration with visual feedback. This sensory modality was also found to be a stronger outcome cue compared to visual and audio. Finally, awareness of intention was impacted by the reliability of receiving haptic feedback. By applying psychological methods to HCI, this interdisciplinary approach also carried implications. Finding the optimal way of integrating mid-air haptics into visual information is key for now, with some general improvements needed in VR. For gesture recognition systems, mid-air haptics is not only viable but maybe even necessary for strengthening SoA particularly under cognitive load. Finally, the general reliability of the touch sensation being perceived should be of consideration.

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