I feel it in my fingers! Sense of agency with mid-air haptics

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***Abstract*— Recent technological advances incorporate mid-air haptic feedback, enriching sensory experience during touchless virtual interactions. We investigated how this impacts the user's sense of agency. Sense of agency refers to the feeling of controlling external events through one's actions and has attracted growing interest from human-computer interaction researchers. This is mainly due to the fact that the user's experience of control over a system is of primary importance. Here we measured sense of agency during a virtual button-pressing task, where the button press caused a tone outcome to occur after intervals of different durations. We explored the effect of manipulating a) mid-air haptic feedback and b) the latency of the virtual hand's movement with respect to the actual hand movement. Sense of agency was quantified with implicit and explicit measures. Results showed that haptic feedback increased implicit sense of agency for the longest action-outcome interval length. Results also showed that latency led to a decrease in explicit sense of agency, but that this reduction was attenuated in the presence of haptic feedback. We discuss the implications of these findings, focusing on the idea that haptic feedback can be used to protect, or even increase, users' experiences of agency in virtual interactions.**

I. Introduction

Touchless interactions enable the user to interact with a system using their hands, without physically touching a device [1]. This removes constraints associated with physical contact and is becoming increasingly common due to several potential benefits. These include enabling sterile interaction during surgery [2], hygienic public displays [3], improving physical rehabilitation interventions [4], fostering higher levels of embodiment [5], and facilitating onboarding into virtual and augmented reality [6].

In the current study, we are interested in the user's sense of agency during touchless interactions in virtual environments. The sense of agency is defined as the feeling of controlling the outside world through one's own actions [7], and has been the focus of a great deal of research in the fields of psychology and neuroscience. In the context of human-computer interaction (HCI) its importance is recognised in Shneiderman and Plaisant's [8] strategies for effective interface design, aiming to emphasise the user's sense of control over a system and its responsiveness.

An increasing number of studies have investigated the sense of agency in the context of HCI, showing, for example, that input modality [9], and assistive input [10] can alter the strength of this experience (for a more extensive review see [11]). In the context of touchless interaction, there are two potential issues for the user's sense of agency: the absence of haptic feedback, and the mismatch between the movement and its visual representation. We explore the effect of both of these in the current paper.

A. *Factors affecting the virtual agent*

One of the key insights from cognitive neuroscience research is that the sense of agency is an experience arising from multiple sources of information, including sensory feedback relating to the movement [12]. According to Moore and Fletcher [13], these sources of information fall into one of two categories – those that are internal to the individual who is acting and those that are external. Internal cues are mainly motor signals generated by the motor system and proprioceptive cues generated by the cells on the body's muscles and joints. External cues include sensory information generated by the environment and also social or situational factors. The sense of agency is based on a combination of these various agency cues, and, importantly, their absence will reduce or distort the user's sense of agency.

In light of this, the absence of haptic information during touchless interaction is likely to have a detrimental effect on the user's sense of agency. This issue is potentially mitigated by the development of mid-air haptic ultrasound technology, which enriches the user's sensory experience. This technology is able to transmit vibrotactile information directly to the hand by using a focused point of ultrasound to create force that stimulates the mechanoreceptors [14]. This can trigger touch sensations in the mid-air while the user is acting with their bare hands, and can accompany already-available sensory feedback (e.g. visual).

Another important insight from cognitive neuroscience research is that a temporal delay between movement and feedback reduces the sense of agency [15]. Increasing this delay also modulates activity in sensorimotor circuits associated with agency [16]. Temporal delays have been found to have a negative impact on agency in the context of HCI, referring to input latency, in tasks such as joystick movement [17] and VR body movements [18], [19]. This suggests the same is true for touchless interaction and the temporal mismatch between the user's hand movements and their visual representation (such as a virtual hand). Latency effects are, to some extent, inevitable, owing to hardware processing delays. However, it is likely that latency (at least of a certain magnitude) will have a negative impact on sense of agency.

The aforementioned neurocognitive research suggests that in comparison to typical physical interaction, sense of agency may be reduced during touchless interaction due to a reduction in haptic feedback. Related research also suggests that the temporal congruency between the actual hand and the

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visual representation of the hand also plays a role in the user's sense of agency. This is something we directly investigated in the present experiment, comparing sense of agency with and without mid-air haptic feedback, and under different latency levels.

B. Measuring sense of agency

The sense of agency has both implicit and explicit aspects [20]. Implicit sense of agency refers to the low-level background feeling of control that typically accompanies our voluntary actions. Explicit sense of agency refers to the high-level conscious judgments of agency that we are able to make about our own actions. To measure the explicit judgement of agency, we used self-report likert scale style questions [21]. To measure the implicit sense of agency, we used a robust, implicit quantitative method called intentional binding, first introduced by Haggard et al. [22]. This measure is based on the observation that voluntary action is associated with systematic changes in the subjective experience of time. More specifically, repeated experiments have shown that voluntary actions are associated with a subjective shortening of the perceived interval between the action and its outcome (see [23], for a review).

The intentional binding phenomenon is illustrated in Figure 1. When an individual performs a simple operant action, such as a key press (action) causing a tone (outcome), they will typically perceive the action as having happened later and the tone as having happened earlier than they actually did. Crucially, the opposite effect is found for involuntary movement. For example, if someone is made to passively press a key that causes a tone, they will typically perceive the action as having happened earlier and the outcome as later than they actually did. This difference in time perception associated with voluntary and involuntary actions is the reason why intentional binding is seen as a valid measure of sense of agency – the binding of the two events is specific to voluntary action.

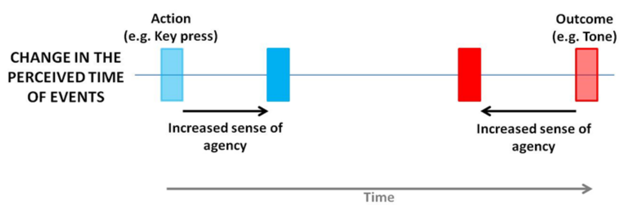

Fig 1. Binding effect is the perceived compression of time between action and outcome, associated with a greater sense of agency.

Different ways of capturing this phenomenon have been developed. One of the most widely used is the so-called Libet clock method [23]. This uses a visual clock stimulus to capture timing judgements. However, the Libet-clock method is not best suited to action contexts in which there are competing visual stimuli in the visual field. This would be the case in our current paradigm where we are presenting a virtual hand. In this way we adopted an alternative measure of intentional binding which simply requires asking participants to estimate the duration of the interval between the action and its outcome [24]. Based on this approach, shorter interval estimates indicate increased binding, which itself indicates a stronger sense of agency. This method overcomes the issues associated with competing visual stimuli. Furthermore, while some intentional binding studies will include a passive control condition, a number of studies simply opt to compare the magnitude of intentional binding across conditions [10], [25], [26]. We have adopted the latter approach, as we are interested in changes in the relative strength of sense of agency as a function of manipulations of latency and haptic feedback.

C. Experiment and hypotheses

We had participants complete a virtual button press that caused an auditory tone after a brief delay. In one condition the virtual button was accompanied by mid-air haptic feedback and in another condition that feedback was absent. Within each of these conditions we also manipulated the latency of the virtual hand's movement, with four levels of latency: 0ms, 50ms, 100ms and 150ms. In light of the literature reviewed above, we arrived at the following hypotheses:

H1: Binding and self-reported agency will be greater when haptic feedback is present

H2: Binding and self-reported agency will be reduced as latency increases

H3: This effect of latency will be attenuated in the presence of haptic feedback

II. METHOD

This study was conducted with ethical approval from the Goldsmiths ethics committee, including updates regarding Covid-19 regulations.

A. Participants

We recruited an opportunity sample of 10 participants (7 males, 2 females and 1 failed to report), 6 of whom participated remotely via Zoom. This was done in order to abide by local covid-19 testing restrictions. Participants were recruited via email and were entered into a £200 amazon voucher raffle. Ages ranged from 23-43 (M=31.2; SD=6.3). All participants were right-handed with a mean laterality quotient of 97.22 (revised Edinburgh Handedness Inventory [27]). There were no self-reported visual impairments. No participants were excluded in their entirety, however two participants' interval estimation data were excluded from the binding analysis (see RESULTS).

B. Tasks and measures

Intentional binding (see Figure 1) was measured via the interval estimation task [24] – a direct estimation of time between action and effect. The interface scene (see Figure 2a) included a virtual button which could be pressed with the tracked virtual hand. When the button was pressed, an auditory tone outcome was played after an interval of either 100ms, 400ms or 700ms. This action-outcome interval range is a typical way of measuring intentional binding. Following the standard intentional binding procedure, participants were not told of the actual interval lengths, and instead were told that it randomly varied between 1 and 999ms across trials. On each trial they were asked to estimate the duration of the interval in ms. Lower interval estimations indicate a stronger binding effect and therefore a stronger sense of agency.

Within the binding task, the virtual hand-button interaction either included haptics or did not, and latency for the movement of the virtual hand was 0ms, 50ms, 100ms or 150ms after the actual hand movement. Interval estimations were entered via a graphical user-interface (GUI) panel which included a text field ("*Enter milliseconds…*") and submit button. This was done with either the keyboard/mouse or the laptop touchpad (depending on the remote setup).

A straightforward explicit measure of agency is to use rating scales to directly tap into the user's explicit judgement of agency during the interaction [21]. Agency comprises two key components – control over the body part that is moving, and causation between action and outcome [7]. As such, two self-report questions were tailored to the task: "I feel in control of the hand movement" and "I feel I am causing the sound by pressing the button". These were measured on a Likert scale from 1 (strongly disagree) to 7 (strongly agree) and were presented 3 times in each condition (every 12 trials).

C. *Apparatus*

The programme was setup, coded and run via Unity engine (v. 2019.3.0). An Ultraleap STRATOS Explore development kit provided the haptic stimuli with included a Leap Motion device for hand tracking (Figure 2b). This device uses ultrasound technology to create focal points on the user's hand which transmits tactile sensations [14]. The focal point targeted the palm area of the hand and created a circle shaped sensation. The sensation was designed to mimic a physical button. The strength of the circle varied during the downward movement of the hand, meaning the haptic sensation ranged from maximum intensity with the button fully extended to no feedback at the point of click. A mouse and keyboard (or laptop) were used for interacting with other UI text fields/buttons on screen.

The Zoom Meetings app was used for video calls during remote participation, so that experimenter instructions could be given throughout.

a) b)

Fig 2. The experimental setup. a) the interface scene of the hand and button. b) a visualisation of how mid-air haptic feedback is provided to the hand and the apparatus setup placement

D. *Design and procedure*

A 2x4x3 within-subjects experimental design was used with the following factors: haptics (with feedback, without feedback), latency (0ms, 50ms, 100ms, 150ms) and actual button press-tone interval (100ms, 400ms, 700ms) (Figure 3).

Preliminary checks (for remote participants) were made to ensure the experimental setup was as instructed (RE: Figure 2b), that participants were using their headphones, and if all necessary executable programmes were downloaded. Participants were told the experiment would involve pressing a virtual button and hearing a sound on each trial. Furthermore they were told that the time interval between the button press and sound will randomly range between 1-999ms and that they should submit an estimate for each interval. Finally, they were told that at times within each block they will be asked to rate how much they agree with statements about their experience.

For the learning phase, the practice block had 10 trials which consisted of pseudorandom intervals of 50ms, 500ms and 950ms; the actual intervals were displayed on screen each trial. This was to get the participant familiar with the millisecond timescale and equipment. Once the practice block ended, participants moved onto the experimental phase. It was reiterated that intervals will now not only be those that were in the practice block, but *any* time between 1-999ms (to reduce anchoring). Also, that experimental blocks will now pause at points in between to rate agreement with the statements.

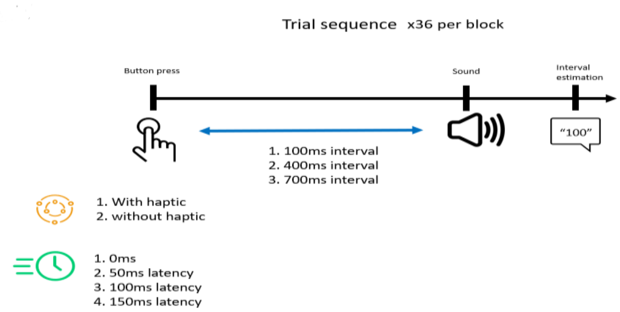

Fig 3. Experiment trial structure. UI screens load for the (keyboard) entering of interval estimates and a second UI screen every 12 trials for self-report questions

Blocks 1-4 were each latency condition with haptic feedback, blocks 5-8 were each latency condition without haptic feedback. Within each block, actual button press-tone intervals varied pseudo randomly (Figure 3). Also, every 12 trials (3 times per block) the scene paused, and participants answered the two self-report questions by clicking a UI button (choices 1-7, from strongly disagree to strongly agree) with their mouse or touchpad. Participants completed either blocks 1-4 (in a randomised order), or 5-8 first, thus ensuring that the order of haptic feedback was counterbalanced across participants. An "End of block" message was displayed at the end of each block, and participants were instructed to close, and open the next block.

After all blocks were completed, participants were debriefed and asked if they had noticed anything during the experiment.

III. Results

Based on a criterion from Moore et al.'s [12] study, two participant's interval estimation data were excluded from analysis due to standard deviations above 300ms across multiple conditions (*NB* this criterion is independent of the dependent variable of interest – mean interval estimation error). Of the remaining participants, interval estimate errors were calculated (estimate-minus-actual) and averaged for each interval and for each condition respectively, so that *lower* scores equal greater binding. Overall mean estimation errors for each condition are shown in Table 2. Self-report answers (*control* and *causation*) were averaged respectively for each condition, with *higher* scores equal to greater agency. Data analysis was conducted in SPSS.

TABLE 1.
Mean interval estimation errors (ms) for each condition with standard deviations in parentheses

	Actual interval					
	100ms		**400ms**		**700ms**	
Latency	**Haptic**	**No Haptic**	**Haptic**	**No Haptic**	**Haptic**	**No Haptic**
0ms	-48.5 (27.2)	-43.3 (50.6)	-226.6 (67.7)	-171.9 (119.6)	-347.3 (158.7)	-263.8 (192.2)
50ms	-25.8 (53.3)	-37.8 (48.0)	-176.9 (80.2)	-169.6 (98.3)	-284.2 (179.4)	-265.6 (193.7)
100ms	-48.6 (36.3)	-33.9 (39.8)	-196.1 (81.3)	-189.3 (123.0)	-342.5 (164.8)	-284.1 (175.9)
150ms	-35.5 (33.9)	-19.2 (46.9)	-195.5 (91.7)	-208.8 (102.9)	-313.8 (148.8)	-271.0 (188.1)

A. Haptics and latency on interval estimation errors (binding)

We conducted a 2x4x3 repeated measures ANOVA with haptic feedback (haptic or no haptic), latency (0ms, 50ms, 100ms and 150ms) and actual interval (100ms, 400ms and 700ms) as experimental factors. This revealed an expected main effect of actual interval, $F(2, 14) = 24.18$, $p = .001$, $\eta_p^2 = .78$, such that estimate error scores monotonically decreased as actual interval length increased (Figure 4). There was no significant main effect of haptic feedback on estimation errors, $F(1, 7) = 3.31$, $p = .112$, $\eta_p^2 = .32$, nor was there a significant main effect of latency, $F(3, 21) = 0.83$, $p = .495$, $\eta_p^2 = .11$. The haptic x latency interaction was also non-significant, $F(3, 21) = 0.38$, $p = .771$, $\eta_p^2 = .05$. There was however, a significant haptic x actual interval interaction, $F(2, 14) = 3.98$, $p = .043$, $\eta_p^2 = .36$, suggesting that the effect of haptic feedback differed, depending on the actual duration of the button-tone interval.

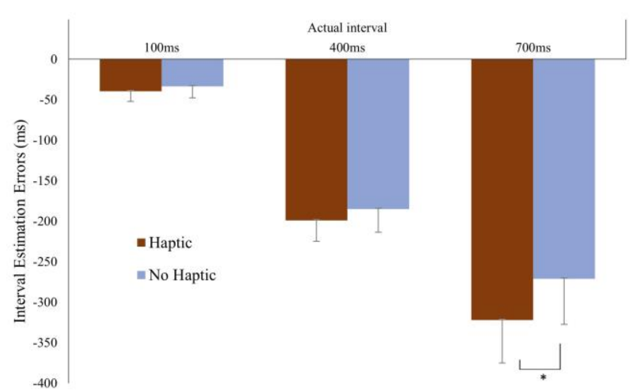

Fig 4. Estimation errors by haptic feedback, at each level of actual interval length. The error bars show SE across participants. * p<.05

To explore this interaction further, *Bonferroni adjusted* pairwise comparisons for haptic x actual interval revealed a significant mean difference ($M_{difference}$=-50.84, p=.039) between haptic and no haptic conditions at the 700ms interval length, such that interval estimation errors were lower (greater binding) when haptic feedback was present (see also Figure 4). Such differences were non-significant at interval lengths 100ms ($M_{difference}$=-6.06, p=.659) and 400ms ($M_{difference}$=-13.87, p=.374). This finding suggests that haptic feedback has a significant positive effect on the implicit sense of agency when the action-tone delay is at its longest.

B. Haptics and latency on self-reported control

A 2x4 repeated measures ANOVA with haptic feedback and latency revealed no main effect of haptic feedback, $F(1, 9) = 3.76$, $p = .084$, $\eta_p^2 = .26$, on self-reported feelings of control (virtual hand). There was a main effect of latency, $F(3, 27) = 3.16$, $p = .041$, $\eta_p^2 = .26$, with a significant linear trend, $F(1, 9) = 5.72$, $p = .041$, $\eta_p^2 = .39$, such that feelings of control monotonically decreased as latency increased. There was also a significant haptic feedback x latency interaction, $F(3, 27) = 3.08$, $p = .044$, $\eta_p^2 = .26$, suggesting the effects of latency on feelings of control varied as a function of haptic feedback.

As planned, a simple effects analysis was run to test the linear trend effect of latency on self-reported control of the hand at the level of haptic feedback, using coefficients of 3, 1, -1 and -3. This analysis revealed that the linear decrease of latency was significant in the no haptic feedback condition, $F(1, 9) = 6.93$, $p = .027$, $\eta_p^2 = .44$, and non-significant in the haptic feedback condition, $F(1, 9) = 1.31$, $p = .283$, $\eta_p^2 = .13$ (Figure 5). Furthermore, *Bonferroni adjusted* pairwise comparisons revealed a significant mean difference ($M_{difference}$=1.10, p=.038) in feelings of control between haptic feedback and no haptic feedback conditions, at 150ms latency (see also Figure 5). This difference was non-significant at 0ms ($M_{difference}$=.133, p=.678), 50ms ($M_{difference}$=.433, p=.077) and 100ms ($M_{difference}$=.300, p=.324) of latency. This suggests that haptic feedback attenuated the latency-induced reduction in self-reported feelings of control.

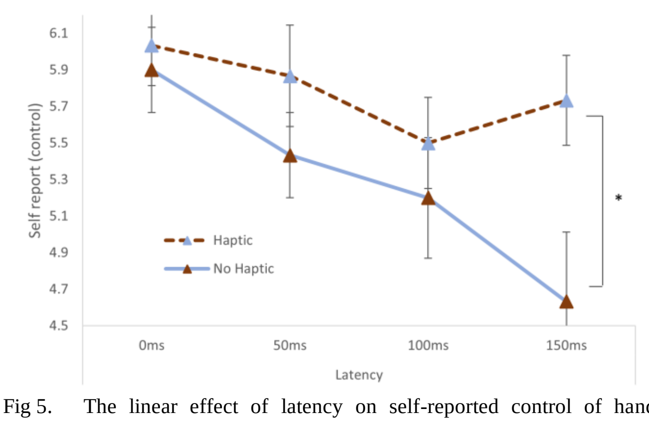

Fig 5. The linear effect of latency on self-reported control of hand modulated by haptic feedback. *p<.05

C. Haptics and latency on self-reported feelings of causation

A 2x4 repeated measures ANOVA with haptic feedback and latency revealed non-significant effects of haptic feedback, $F(1, 9) = 1.63$, $p = .233$, $\eta_p^2 = .15$, and latency, $F(1, 9) = 1.62$, $p = .207$, $\eta_p^2 = .15$, on self-reported feelings of causation. The haptic feedback x latency interaction term also yielded a non-significant result, $F(3, 27) = 1.90$, $p = .153$, $\eta_p^2 = .17$. As none of these effects were significant, further simple effects and pairwise comparisons were not conducted.

IV. Discussion

The current study measured sense of agency in touchless interactions. An implicit measure (intentional binding) and an explicit measure (self-report) were used to measure the effect of haptic feedback and latency of the visual representation of the virtual hand on the sense of agency during these interactions. Overall, our hypotheses were partially supported. Contrary to our initial hypotheses there was no overall difference in sense of agency in the haptic vs. no haptic conditions. However, there was greater implicit sense of agency with haptic feedback at the 700ms action-outcome intervals. Second, while latency between the real hand movement and the virtual hand representation had no effect on intentional binding, there was an effect on explicit sense of agency. Namely, self-reported control of the virtual hand representation decreased as latency increased from 0ms–150ms. Furthermore, this effect of latency on sense of agency was reduced when haptic feedback was present. That is, even as latency increased, feelings of control over user representation were maintained if haptic feedback was present.

A. Haptic information and human-computer interactions

Making actions through virtual controls (such as a button) cause context relevant events to occur in virtual and augmented environments. Feeling like the agent for the events one causes is critical for many contexts, as with the real world. The present study added haptic cues to the virtual button that was accompanied with visual feedback. Evidence here supports previous literature demonstrating the binding effect for mid-air hand tracked interfaces [28]. This study differs experimentally to previous work [28], which applied an abstract haptic cue as the outcome of an action (post-interval). In contrast to this the present study provided haptic cues to the actual control point (the button) and kept the outcome constant, in the form of an auditory tone.

Here, we found that haptic cues increase the implicit sense of agency at longer action-outcome interval delays. This suggests that visual cues may be sufficient for the sense of agency for shorter causal events but for longer-term causal events, additional haptic cues increase binding between the user's action and outcome. Recent research supports this idea, indicating that visual binding breaks down with longer outcome delays [29], [30]. These findings may be explained by the cue integration approach put forward by Moore et al. (see [12], [13]), suggesting cues are weighted based on their reliability. For example, it might be that visual information at shorter action-outcome intervals is given a higher weighting and that the addition of haptic information contributes little to agentic experience in this context. However, as these intervals increase, and the visual information is rendered less reliable, it may be that the weighting of haptic information increases, thus furnishing the user with a greater sense of agency.

This is an exciting avenue for HCI research because it provides empirically grounded suggestions for multisensory interface design. Multimodal feedback has been proposed as beneficial when systems experience connection-speed restrictions [31]. This notion is supported here such that the addition of mid-air haptic feedback increases agency at longer action-outcome interval delays. As such, actions and their effects can be expected to vary in time with ongoing hand-tracked interaction, and haptic cues accompanying visuals may help to optimise feelings of control throughout the experience.

B. Input latency and haptic information

Previous studies have investigated the effect of latency on explicit agency judgements in VR [18], [19]. The current research is the first, however, to our knowledge, exploring the impact of latency on the sense of agency using both implicit and explicit measures. Input latency means that when the user moves their hand, the virtual hand (or other hand representation) moves sometime after they have actually moved. Depending on the task, this can potentially negatively impact the sense of agency. The findings of this study showed that the explicit sense of agency deteriorated with increasing latency. This is useful for interface designers to consider when making decisions about what hardware to use in an experience, in that self-reported control of a virtual hand begins to deteriorate with latency as low as 50ms.

Predictive visual cues have been shown to partially mitigate the negative effect of input latency on agency over joystick movement [17]. Similarly, here we found that the negative effect of latency for the virtual hand on self-reported control was mitigated by haptic feedback. This suggests that mid-air haptic feedback allows one to maintain sufficient feelings of control over virtual user representation where it otherwise breaks down. Parameters regarding the trade-off between system reliability and latency [11] are informed here. With the presence of haptic feedback, VR input methods may have more room to accurately input the user's intention and provide more reliable feedback.

C. Limitations and future direction

The first limitation concerns the lack of a passive control condition in our experiment. Although our design allowed for the relative comparison of sense of agency between conditions, a passive control condition would have permitted stronger claims regarding the absolute presence or absence of sense of agency. Despite this limitation the approach we have adopted here remains informative and has been used widely in previous studies [10], [25], [26].

A second limitation relates to the possible effect of latency on the agentic structure of the task. By adding latency between actual movement and its visual representation, it may be that the delayed visual representation was perceived as an intermediate outcome. This would mean the action was regarded as having two outcomes. Importantly, previous research has shown that binding is weaker for the second outcome [32]. However, although this may be a confound, it is important to note that we did not find a reduction in intentional binding when latency was increased.

A third possible limitation is that the explicit report questions were preceded by action-outcome intervals of different lengths. This is because the questions were presented at a fixed point in each block of trials, but the trials themselves were pseudorandomly presented. Therefore, the explicit question could follow an action-outcome delay of 100, 400 or 700ms, and we were not able to control for this. It is possible that explicit reports of control were influenced by the interval in the immediately preceding trial – perhaps participants were more likely to report greater control following a short action-outcome interval. Although this is possible it is important to note that this was effect was random and therefore unlikely to confound the results.

A final limitation concerns the focal point for haptic feedback. In our experiment the haptics' focal point for the button was the palm area, and participants were instructed to press using their palm. Future experiments could use more stringent haptics for the finger, closer to that of buttons used in typical binding studies.

V. Conclusion

In sum, we have explored users' sense of agency over a virtual button pressing task, focusing on the role of mid-air haptic feedback. Our results showed that mid-air haptic feedback can have two possible effects: promoting implicit sense of agency for longer action-outcome intervals, and protecting against latency-induced reductions in the explicit sense of agency. These findings are likely to be of considerable interest to those working with these technologies. Not only do our results show that it is possible to precisely and quantitatively pinpoint important changes in the user's experience of control in VR, but also that these changes can be modified or improved through the use of mid-air haptic technology.

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