Mid-air haptic congruence with virtual objects modulates the implicit sense of agency

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Abstract. Hand-tracking technologies allow interactions with virtual environments unmediated by any physical tool. Mid-air haptic technologies further this interaction paradigm by providing the user with tactile feedback. As an additive sensation not strictly bound to physical-based laws of objects, there is much room for exploration of various integration methods. Here, we investigate whether the psychological variable known as the sense of agency (SoA) is sensitive to variations of a mid-air haptic stimulus, where SoA captures the user's feeling of control and causal influence in the virtual environment. To that end, we use a virtual button press-tone (action-effect paradigm) to measure SoA at the behavioural level as well as through self-report. Mid-air haptics accompanying the visual element of the virtual button press were varied at 4 levels: dynamic, fixed, on completion and no feedback. Results show a significant influence at the behavioural level but were not self-reported. Additive mid-air haptics that was not congruent with the visual elements negatively impacted the implicit feeling of SoA.

Keywords: Mid-air haptics, Congruence, Sense of agency, Virtual reality

1 Introduction

Hand-tracking systems allow users to interact with a variety of cyber-physical objects or widgets without the mediation of a physical tool such as a games controller, a physical button, touchscreen, or joystick. This method of direct object manipulation and control can be used in environments such as medical settings [1], animation and editing [2], motor rehabilitation [3], car menu navigation [4], or even in everyday public settings [5]. Despite these systems offering more natural and hygienic modes of interaction, one significant drawback is the absence of haptic feedback [6]. To remedy this issue, ultrasound mid-air haptic technology has been developed which is able to deliver touch sensations when users perform gestures in mid-air [7].

Not only does haptic feedback replicate the sensations associated with action, but there is growing evidence that it also supports the sense of agency (SoA). SoA refers to the feeling of control over actions and their effects, and is considered important to human-computer interaction [8]. Within the context of touchless interfaces, research has shown that mid-air haptic feedback evokes a stronger SoA when compared to visual feedback [9]. Furthermore, Evangelou et al. [10] looked at the contribution of haptic feedback to SoA over a mid-air button press interaction in a virtual environment under varying conditions of hand-tracking latency. Results showed that the beneficial effects of haptics only became apparent as the latency increased. This would suggest a more protective factor such that mid-are haptic feedback sustains the user's experience of SoA when visual information regarding bodily movement becomes unreliable.

The aforementioned research has focused on the presence and absence of mid-air haptics, and the congruence of visual feedback. Here, we investigate whether different types of mid-air haptic feedback accompanying a virtual button press affects SoA. To study this effect, we used an *implicit* measure of SoA known as intentional binding [11]. This refers to the finding that the interval between an action and its effect is perceived as closer together in time when the user feels in control of the action. We also measured *explicit* judgements of agency using self-report. We 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 Method

2.1 Participants

Based on a previous study [10], 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 [12] 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.

2.2 Materials and apparatus

An interactive non-immersive virtual scene (see Figure 1) 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 [13], and provided haptic feedback for the virtual button (Figure 2b). A haptic sensation for the button was designed for each condition (Figure 2a): *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 [14].

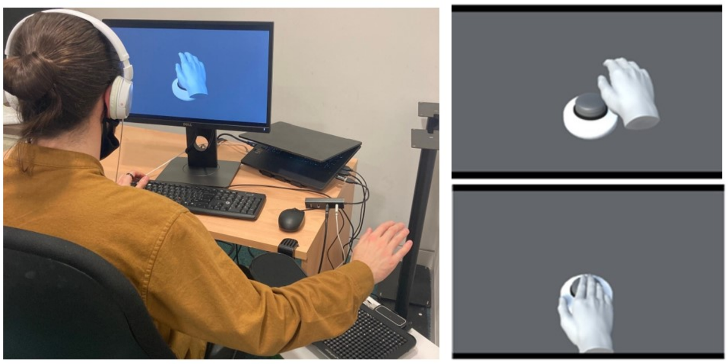

Fig. 1. Apparatus setup and virtual scene perspective

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.

2.3 Measures

To measure implicit SoA, we used the interval estimation version of the intentional binding paradigm [15]. 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 2c), while participants were told the range could be from 1-1000ms. Shorter interval estimates are taken to indicate a stronger SoA [11].

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. [16] 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).

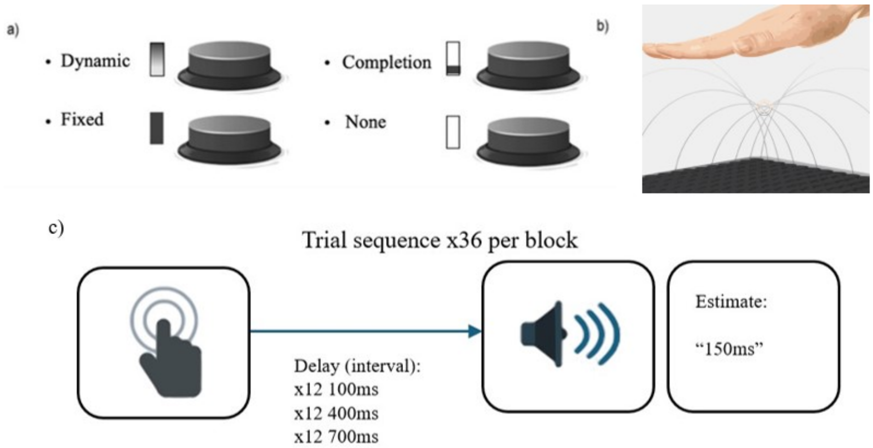

Fig. 2. a) Mid-air haptic types b) Representation of mid-air haptics c) Experimental block and trial structure

2.4 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 2c).

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 trials at the beginning 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.

3 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:

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

where χ^2 is the test statistic, N is the total sample size and p – 1 is the degrees of freedom [17]. Holm-Bonferroni corrections for Durbin-Conover post-hoc tests set alpha level to:

$$\alpha = .05/(m - k + 1) \tag{2}$$

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

3.1 Haptic 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 3), 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.

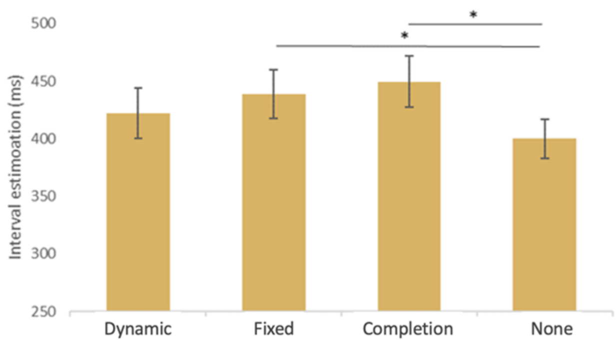

Fig. 3. Mean interval estimations per condition. Lower scores indicate greater agency. Error bars represent standard error across participants.

3.2 Haptic feedback on self-report agency

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

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

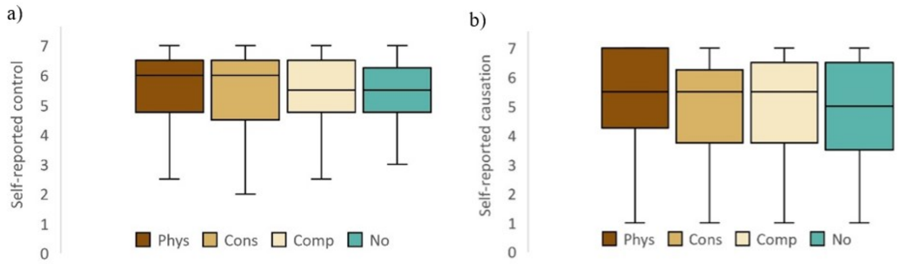

Fig. 4. Ratings of a) control over the button press and b) causal influence over the tone plotted as a function of mid-air haptic type. The middle lines of the boxplot indicate the median; upper and lower limits indicate the first and third quartile. The error bars represent 1.5 X interquartile range or minimum or maximum.

4 Discussion

Different types of mid-air haptics accompanying a virtual button press did not affect explicit judgements of agency. However, they did influence implicit sense of agency as revealed by changes in the perception of time between the action and its effect. These findings indicate that subtle differences in mid-air haptics can modulate SoA at the implicit but not explicit level. More specifically, while SoA was maintained with the dynamic haptic press, it did drop off with fixed and completion-only haptics. This suggests that when integrating mid-air haptics in virtual environments, their congruence with the visual elements of feedback is important for maintaining the subjective feeling of agency.

Previous literature states that having agency over a haptically incongruent event overcomes any negative effects on user experience [18]. Intriguingly our study offers a slightly different perspective on this issue, suggesting that haptic incongruence can negatively affect the user's 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 implicit SoA, revealing a negative effect on user experience. While even the integration of congruent haptics did not necessarily have a positive effect over and above just the visual element, it was comparable for the agent nonetheless. Given mid-air haptics has been shown to improve other user experience factors such as engagement [19] and clarity and enjoyment [20], its appropriate integration is evidently beneficial overall.

Interestingly this was not observed at the explicit level - judgements of causation were not significantly affected. This difference between explicit and implicit aspects of agency is something that has been demonstrated in previous research showing that visual incongruence negatively impacts explicit but not implicit SoA [16]. It may be that more obvious visual differences are salient and therefore explicit to the user, while more subtle haptic differences have an implicit influence below the level of awareness. This is also consistent with the broader conceptual distinction between these levels of SoA [21].

In sum, we investigated whether the subjective experience of agency is sensitive to the addition of different mid-air haptics in a virtual environment. Explicit SoA remained unaffected, however the implicit feeling of SoA was negatively impacted by precise yet incongruent forms of haptics. It appears subtle differences in mid-air haptics influences this experience below the level of awareness, or at least this is the case in our simple button-press paradigm. Future research could aim to directly compare this difference in impact between haptic and visual manipulations on the explicit judgement and implicit feeling of agency. Indeed, mid-air haptics can be designed in a multitude of spatial and temporal combinations using recently developed authoring tools [22]. We conclude with the suggestion that care should be taken to appropriately match haptic and visual feedback in a way that best supports users' sense of agency.

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Declaration of interests. This research is part of a collaborative studentship with Ultraleap Ltd. Orestis is a member of *IEEE*.

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