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The Temporal Limits of Agency for Reaching Movements in Augmented Virtuality

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Abstract—**The sense of agency (SoA) describes the feeling of being the author and in control of one's movements. It is closely linked to automated aspects of sensorimotor control and understood to depend on one's ability to monitor the details of one's movements. As such SoA has been argued to be a critical component of self-awareness in general and contribute to presence in virtual reality environments in particular. A common approach to investigating SoA is to ask participants to perform goal-directed movements and introducing spatial or temporal visuomotor mismatches in the feedback. Feedback movements are traditionally either switched with someone else's movements using a 2D video-feed or modified by providing abstracted feedback about one's actions on a computer screen. The aim of the current study was to quantify conscious monitoring and the SoA for ecologically valid, three dimensional feedback of the participants' actual limb and movements. This was achieved by displaying an Infra-Red (IR) feed of the participants' upper limbs in an augmented virtuality environment (AVE) using a head-mounted display (HMD). Movements could be fed back in real-time (46ms system delay) or with an experimental delay of up to 570ms. As hypothesized, participant's SoA decreased with increasing temporal visuomotor mismatches (p<.001), replicating previous findings and extending them to AVEs. In-line with this literature, we report temporal limits of 222±60ms (50% psychometric threshold) in N=28 participants. Our results demonstrate the validity of the experimental platform by replicating studies in SoA both qualitatively and quantitatively. We discuss our findings in relation to the use of virtual and mixed reality in research and implications for neurorehabilitation therapies.**

Keywords—augmented virtuality; sense of agency; presence; sensory integration; movement feedback; motion capture

I. INTRODUCTION

Acting and interacting with our environment and other invididuals are fundamental aspects of our human experience. Generally taken for granted, our ability to do so depends on i) a clear delineation of our own body as separate of others as well as the environment, and ii) the capacity to attribute actions and their outcomes to the correct entity. The former concept is usually referred to as the sense of (body) ownership, the latter as the sense of agency, i.e. the feeling of being the author of your movements, actions, and thoughts [1]. These processes largely function outside of conscious awareness but can have severe consequences, if perturbed as illustrated e.g. by delusions of control in individuals diagnosed with schizophrenia [2].

Body ownership and agency are usually investigated by creating a sensorimotor mismatch between a participants' actual limb position or movement and the provided (audio-) visual feedback. Such studies have illustrated the malleability of body representation and its reliance on multisensory and sensorimotor congruence [3], [4]. Moreover, a series of studies have exploited this dependence to investigate body ownership using the now ubiquitous Rubber-Hand Illusion [5]. As the name implies, the illusion relies on hiding the participants' actual hands from view and replacing them with artificial replicas (with varying level of detail and actual limb resemblance). Similarly, SoA is generally investigated by giving participants a goal-directed task such as drawing a line, performing a specific gesture, or walking into a target location and using feedback that is either switched using video [6], abstracted by providing only positional feedback [7], or relayed by mapping the movements onto a virtual representation of the limb or body [8]. Importantly, it has been shown that familiarity with an observed action [9] and attribution of that action to oneself or another [10] affects how we process these actions and which cortical areas are involved [11]. These findings at least allow us to question the reliance on the aforementioned 'alienated' visual stimuli and their ecological validity.

The current study therefore has two aims: one, to investigate the use of augmented virtuality in ownership and agency research by transferring the participants' own limbs into the virtual environment, and two, to validate this method by qualitatively and quantitatively replicating previous studies investigating the sense of agency. To this end we created a goal-directed reaching task in which we asked participants to reach for a virtual ball with their actual hand, now visible in the virtual environment. Feedback was presented in real-time or with a randomised delay of up to 570ms. SoA was quantified by asking participants to rate the veracity of the feedback after each of the 90 trials (forced choice 'yes'/'no' reply) and extracting the psychometric thresholds at 50%. This represents the temporal limit of the SoA and the delay threshold after which participants no longer perceive the majority of the feedback to reflect their actual movement. We hypothesised that participants' SoA would decrease with increasing sensorimotor mismatches and yield temporal thresholds in-line with previously reported findings.

II. METHODS

A. *Materials*

1) Head Mounted Display

The Oculus Rift DK2 (Subsidiary of Facebook, Menlo Park, CA, USA), Version 1.6 (SDK 0.5.0.1), was used to present the visual stimuli. The HMD has a resolution of 960x1080pixels per eye, a horizontal field of view of 100º, and a refresh rate of 60Hz. The HMD by itself weighs 440g. As participants were asked to keep their head stationary during each trial only head orientation was tracked.

2) Hand Tracking

The LeapMotion controller (Leap Motion, Inc. San Francisco, CA, USA) Software Version 2.3.1 was used to track upper limb movements. The device consists of two cameras and three infrared LEDs which track light outside the visible spectrum with a wavelength of 850 nanometres. The visual stimuli used the IR pass-through feed, i.e. no rigs were used to map the IR feed onto a virtual representation. The hardware has an average latency of 8.6ms according to the manufacturer.

3) Laptop and GPU

A MacBook Pro Retina by Apple (Apple Inc., Cupertino, CA, USA), was used to render the visual feedback. The laptop had a dedicated AMD Radeon R9 M370X graphics card.

4) Unity Version 5.1

The Unity 3D game engine was used to link the Oculus Rift and Leap Motion controller. Leap Motion Unity assets were used to represent the users' hands, which have enough fidelity to show fingers, the palm, and the forearm. The augmented hands did not have to be scaled as they were based on the IR pass-through feed.

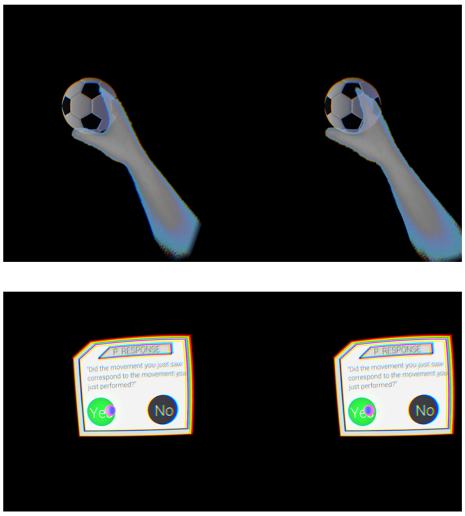

Figure 1 The top panel illustrates the feeback presented to the left and right screens of the HMD (cropped from original ratio). Participants reached for the virtual ball using their augmented IR hand. Feedback could be presented in real-time or with a delay of up to 570ms. Agency replies were collected after each trial by orienting the head towards the 'yes' or 'no' button as indicated by the spherical pointer (lower panel).

B. *Augmented Virtuality Environment*

We designed a minimalistic virtual environment that allowed participants to see the IR-feed of their hands in the VR space. User interaction was achieved through movements of the hands and collision detection, e.g. with the virtual ball, as well as through a gaze based interface as described below. The IR feed could be delivered in real-time or buffered by up to half a second.

1) Augmented Hands

The Image Hand asset is a blend between Augmented Reality (AR) and Virtual Reality (VR). It allows displaying images of participants' real hands from the camera sensors with the (optional) physicality and interactivity of motion-controlled 3D hands. Importantly, only the IR image hands were used in the current setup as illustrated in Figure 1. This differs from previous studies as the participants see their own hands and movements in full detail avoiding mapping or rigging these onto a 3D hand model with only a subset of the availabe degrees of freedom (DoF).

2) Head-Orientation Based Interface

A head-oriented based interface was implemented to allow participants' to respond to the 'yes'/'no' SoA question at the end of each trial, see Figure 1. This type of interface was achieved by using the standard OVRCameraRig to CenterEyeAnchor object. The script uses raycasting, requiring the canvas to be in world-space, and had a Graphic Raycaster attached. This provided a convenient way of extracting head-orientation direction and providing input from the raycast collision.

3) Temporal Delay – Movement Buffer

In order to change the delay of the movement feedback from 0ms to 500ms a frame buffer of the IR-feed was required. Leap's Controller object within Unity maintains a frame history buffer of 60 frames. Hence, calling Controller.Frame() provides the most recent frame, calling Controller.Frame(10) the tenth most recent frame, and so on. At 120fps sampling, this provides up to half a second delay, far above previously reported SoA thresholds. For longer delays, a custom buffer was created that could feed into the HandController instead, creating the delayed movements.

4) Data Logging

Variables logged in this pilot study included a) the SoA answers, b) actual Leap frame rate (averaged over each trial), c) the number of frames delay. Header information further included a date and time-stamp and was saved in a .csv file.

5) System Latency

We calculated the overall latency of the system based on the tracking camera frame rate (120fps, ~8ms), tracking algorithm (4ms), display refresh rate (60Hz, ~17ms), and GPU calculations (1frame, ~17ms). Overall this leads to a maximum latency of 46ms. It is worth noting that our current setup sees numbers very close to those provided by the hardware providers due to the simplicity and lack of geometry in our virtual scene. More complex environments may have to account for more processing frames.

C. Participants

Forty undergraduate students from the University of Central Lancashire participated in the study. Data of N=28 participants were used in the final analysis. Twelve participants were removed from analysis as the experimental script was adjusted and the instructions standardized (see below). Participants were pre-screened, to avoid adverse effects during VR immersion, before giving informed consent. The study was approved by the University's PSYSOC Ethical Committee in accordance with the Declaration of Helsinki.

D. Experimental Procedure

In-line with previous research on conscious movement monitoring and investigations into the SoA participants performed a goal-directed reaching movement at the end of which they were asked to answer the forced choice (yes/no) question: "*Did the movement you saw correspond to the movement you just performed?*" (cf. [6], [8]). Pseudo-randomised spatiotemporal mismatches were introduced in the visual feedback provided to the participants. In the current study, participants were asked to reach out and grasp a virtual ball in front of them. They were asked to lift their hand up from a resting position, bending at the elbow, and then reaching out to touch the ball at a moderate but self-selected speed. This was done to achieve comparable movement patterns across participants and prevent ballistic movements. The position of the virtual ball was kept stable throughout the experiment. The study consisted of three scenarios, namely familiarisation, training, and the experimental block, as explained in the following.

1) Familiarisation with Environment

In order to familiarise participants with the Augmeented Virtuality Environment (AVE), they were given time to explore the feedback of their IR hands in an empty environment. They were given up to 5 minutes but allowed to continue to the training session sooner. Familiarisation feedback was provided in real-time.

2) Training Session

The training session consisted of twelve trials with randomized delays of 63, 138, or 279ms (2, 11, or 28 frames). Participants were asked to report their answer to the experimenter and explain their decision. This was done to ensure participants fully understood the task. Should a participant not be comfortable at the end of the training session this part could be repeated.

3) Experimental Block

The experimental block consisted of 90 randomized trials with 0 – 59 frames delay corresponding to approximately 46ms – 570ms, see table 1; thirty of these trials had no frame-delay. Participants performed the reaching task and answered the SoA question after each of the 90 trials. They were given the opportunity to take a break at any point but no one took up the offer. The main block lasted less than 15minutes and the entire study was generally finished after approximately 30 minutes.

E. Data Analysis

A repeated measures ANOVA with independent variable Delay (seven levels) was conducted on the dependent variable Agency using IBM SPSS. Greenhouse-Geisser correction was applied to the ANOVA results. Post-hoc paired t-tests were corrected for multiple comparisons. Furthermore, psychometric thresholds were calculated by fitting a cumulative Gaussian to the agency responses using the psignifit toolbox [12], [13] for MATLAB (MathWorks, Natick, MA). This enforces bootstrapping algorithms and weighs the individual data points based on the number of valid trials per stimulus intensity. All thresholds reported here reflect the 50% point of subjective equality.

TABLE I. TEMPORAL DELAYS AND SOA REPLIES

	Temporal Delay						
Exp. Delay [frames[a]]	***0***	***8***	***16***	***24***	***32***	***40***	***59***
Total Delay [ms]	46	117	189	259	331	401	570
Agency Replies [%No μ±σ]	9 ±10	16 ±20	48 ±23	67 ±22	79 ±20	90 ±13	96 ±7

a) LeapMotion frames

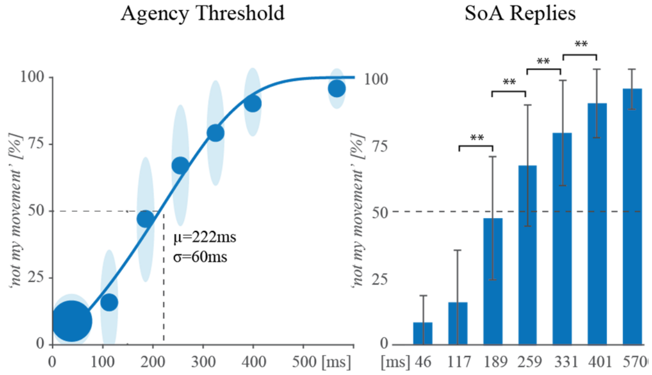

Figure 2 Both panels indicate the monotonous decrease in SoA as a function of the increasing temporal delay (abscissa). As illustrated in the left panel, agency thresholds (50% subjective equality) were calculated, for each participant, by fitting a cumulative Gaussian distribution to the weighted SoA replies. Right panel: SoA replies grouped by delay (error bars are ±1SD). Participants clearly identified with real-time feedback and correctly rejected feedback with large temporal delays.

III. RESULTS AND DISCUSSION

We hypothesised that the sense of agency would depend on the spatiotemporal congruence between the actual movement and the provided visual feedback and therefore monotonously decrease with increasing delays. Furthermore, we expected psychometric thresholds to replicate previously reported findings, thereby demonstrating the validity of the novel, experimental platform.

A. Agency depends on temporal congruence

As hypothesised, the repeated measures ANOVA revealed a significant effect of Delay on the reported SoA ($F(3.68, 27)=158.23$, $p<.001$, $\eta^2=.85$). SoA monotonously decreased with increasing temporal delays, Table 1. Post-hoc analysis revealed that these changes in SoA were significant at $p<.01$ level for comparisons between delay pairs 8/16, 16/24, 24/32, and 32/40 (corrected for multiple comparisons), see Figure 2.

B. *The temporal limits of agency*

Psychometric thresholds, individually extracted for N=28 participants, yielded an average 50% threshold of 222±60ms. This is slightly higher than the 150ms reported in [14] using a simple 50% cut-off, but within the range of previously reported psychometric thresholds of 210ms±26 [8]. This indicates that the current setup not only qualitatively but also quantitatively replicates previous SoA studies and provides a novel platform to investigate aspects of corporeal awareness using the participants' actual limbs rather than an abstracted or disembodied representation of their actions.

C. *Virtual & augmented reality in research and rehabilitation*

Virtual reality methods are becoming increasingly important for research, therapy, and rehabilitation as they can provide a highly adaptable, yet strictly controlled work space [15], [16]. Complementing previous approaches, the current augmented virtuality environment may prove particularly fruitful for research into aspects of embodiment and corporeal awareness by integrating the participants' own limbs, allowing them to interact with the virtual environment: it has been shown that observing an action facilitates the brain's motor circuits involved in performing the same action [11] and this has been reported to depend on the familiarity with the observed action [9] and whether one attributes that action to oneself or another [10]. In the current setup we cannot only investigate under what conditions one recognizes one's own movements as self-generated but further how this depends on the ecological validity of the virtual body. Participants viewed their own hands rather than a generic 3D model with limited DoF or even an abstracted feedback. This conceptually differs from previous studies into corporeal awareness as information about the participants' own limbs, in their actual position, can be manipulated without the introduction of a supernumerary artificial limb. This is hence an important distinction when discussing the sense of agency [17] as well as body ownership [3], [5], [18] and the concept of presence in virtual and mixed reality environments [19].

IV. CONCLUSION

In conclusion, the aims of the current study were twofold: aim one was to pilot the augmented virtuality environment and assess its potential use as an experimental platform; aim two was to replicate previous SoA studies while extending their findings by providing feedback of the participants' own arms in a three-dimensional virtual environment. Our results illustrate that we could systematically modulate the participants' perceived SoA by varying the temporal visuomotor mismatch in the feedback, replicating previous research qualitatively and quantitatively. Importantly, these data demonstrate that the fully immersive environment used here provides a viable platform for investigating core aspects of corporeal awareness and may be a valuable asset in neurorehabilitative therapies.

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