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Sensorimotor experience in virtual reality enhances sense of agency associated with an avatar

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1. Introduction

Virtual reality (VR) has been gaining popularity in diverse fields such as gaming, stream media, industry, and education (Psotka, 1995; Ryan, 2015; Saposnik et al., 2010; Zyda, 2005). People can immerse themselves in a 3D virtual environment and receive compelling multisensory experience with cues from different modalities such as vision, touch, and audition. More importantly, when interacting with the virtual environment, people often possess a virtual representation of their own body (i.e., avatar) whose motion is controlled in synchrony with their real movements. Controlling an avatar can affect people's attitudes and behaviors and some of these effects even last after VR experience and extend to real life (Aymerich-Franch, Kizilcec, & Bailenson, 2014; Blascovich et al., 2002; Fox, Bailenson, & Tricase, 2013; Guegan, Buisine, Mantelet, Maranzana, & Segonds, 2016; Rosenberg, Baughman, & Bailenson, 2013; Yee & Bailenson, 2007; Yee, Bailenson, & Ducheneaut, 2009; Yoon & Vargas, 2014). For instance, after VR experience with an inventor avatar, engineer participants performed better in brainstorming in the real-life scenario (Guegan et al., 2016). Thus, studies in social psychology have convincingly shown that interacting with avatars in immersive VR can affect self-perception.

Similarly, previous studies have shown that experience in VR influences people's self-consciousness, particularly their sense of ownership (SoO) and sense of agency (SoA). SoO refers to the recognition of oneself as the owner of one's body. SoO has been extensively investigated using the rubber hand illusion paradigm. In its original form, when two brushes stroke someone's concealed hand and a visible artificial hand synchronously, people generate a strong feeling of ownership of the artificial hand (Botvinick & Cohen, 1998). This (mis-)attribution of bodily ownership to an external entity has been recreated in VR. In so-called virtual hand illusion, people perceive virtual effectors (virtual hand) as part of their own body after receiving the same stimulation as the real hand or controlling it in immersive virtual reality (Kilteni, Normand, Sanchez-Vives, & Slater, 2012; Ma & Hommel, 2012, 2015a, 2015b; Perez-Marcos, Sanchez-Vives, & Slater, 2012; Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010; Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives 2008; Suzuki, Garfinkel, Critchley, & Seth, 2013; Zhang, Ma, & Hommel, 2015). This type of SoO illusions can even extend to the whole body with VR exposure (Ehrsson, 2007; Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Llobera, Sanchez-Vives, & Slater, 2013; Maselli & Slater, 2013; Petkova & Ehrsson, 2008; Slater, Pérez Marcos, Ehrsson, & Sanchez-Vives, 2009; Slater, Spanlang, Sanchez-Vives, & Blanke, 2010). VR-induced SoO illusions are evidenced both by subjective reports such as questionnaire results (Kilteni et al., 2012; Lenggenhager et al., 2007; Llobera et al., 2013; Ma & Hommel, 2012, 2015a, 2015b; Maselli & Slater, 2013; Petkova & Ehrsson, 2008; Sanchez-Vives et al., 2010; Slater et al., 2008; Zhang et al., 2015) and by objective measures such as proprioceptive shifts (Lenggenhager et al., 2007; Perez-Marcos et al., 2012; Slater et al., 2008; Zhang et al., 2015), modified skin conductance response (Ehrsson, 2007; Ma & Hommel, 2012, 2015a; Petkova & Ehrsson, 2008; Zhang et al., 2015) and heart rate deceleration (Maselli & Slater, 2013; Slater et al., 2010).

However, experimental evidence of how SoA is affected by avatar are mostly based on subjective reports. SoA refers to the experience of controlling one's own actions and their consequences (Haggard & Chambon, 2012). Previous studies on SoA in VR

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typically used questionnaires to ask participants about how confident they were that they controlled the avatars (Kokkinara, Kilteni, Blom, & Slater, 2016; Kokkinara, Slater, & López-Moliner, 2015; Ma & Hommel, 2015b; Nahab et al., 2011; Tieri, Tidoni, Pavone, & Aglioti, 2015). Not surprisingly, all of these studies have reported significantly higher scores of controllability of the avatar when the avatar is controlled synchronously, actively, consistently or with resemblance to physical body as compared to otherwise (Kokkinara et al., 2015, 2016; Ma & Hommel, 2015b; Nahab et al., 2011; Tieri et al., 2015). However, measuring agency by questionnaires is subject to cognitive biases and is largely dependent on task demands. Hence, objective measures of SoA should be employed to address the problem. Recently, Slater and colleagues provided objective albeit indirect evidence for the effect of avatar onto SoA (Banakou & Slater, 2014). After controlling an avatar from a first-person perspective, participants biased their fundamental frequency of utterance towards that of the avatar.

Here we examined whether moving with an avatar in immersive VR can change people's SoA with an objective measure. We used the intentional binding paradigm, which provides a reliable implicit measure of SoA (Haggard, Clark, & Kalogeras, 2002; Moore & Obhi, 2012). The intentional binding task is a temporal judgment task that typically involves an action, either voluntary or involuntary, and a delayed action outcome such as a tone (Haggard et al., 2002; Moore & Obhi, 2012). Voluntary actions, in contrast to involuntary ones, elicit a binding effect such that the perceived time of the action is delayed (biased towards the outcome) while the perceived time of the outcome is advanced (biased towards the action). From a first-person perspective in an immersive VR environment, our participants observed a single movement of their avatar's right hand and then, 250 ms later, a tactile stimulus was delivered to their left hand. Using a Libet clock, they reported the timing of the tactile stimulus. We found a significant binding effect when participants donned their avatar at the very beginning of the experiment and before extensive VR exposure, suggesting embodiment rapidly elicits SoA changes. Importantly, after controlling the avatar to perform goal-directed tasks for 20 min, participants exhibited a stronger binding effect, which reached the level of self-generated actions in a real environment.

2. Materials and methods

2.1. Materials

Participants sat at a desk and wore a head-mounted display (HMD, Oculus Rift DK2). The HMD was equipped with a dual display which gave a combined 90° horizontal and 60° vertical field of view, under a resolution of 960 × 1080 per eye. The latency of the video streamed into the HMD was 50 ms, and the refreshing rate was 60 Hz. Participants wore an inertial-based motion tracking system (Perception Neuron, Noitom; sampling rate 100 Hz) on their right arm to record their arm and finger movements. Occasionally, we delivered a brief vibrotactile stimulus to the left hand of the participant via a piezoelectric actuator (PL140, Piceramc Inc., Germany). The actuator was controlled by a customized controller and driven by a 15 V accumulator power source.

The virtual environment included a room, a desk, and one or two avatars, depending on the experimental conditions (Fig. 1). The virtual desk was spatially aligned with the real desk in front of the participant. While seated, the participant controlled the upper-arm motion of an avatar from a first-person perspective in real time. In some conditions (see below), the participant was faced with a male avatar standing 1.5 m in front of the virtual desk. When participants performed the intentional binding task, they placed both of their hands comfortably on the desktop. A piezoelectric disc delivered a vibrotactile stimulus to their left index fingers when needed. All data acquisition and visual rendering of the virtual scene were controlled by a desktop computer (CPU: i7-3770, graphics card: NVIDIA Quadro FX1500). The virtual environment, the delivery of the tactile stimuli, and the motion tracking were controlled by a customized program implemented on the Vizard 5 platform (WorldViz, Santa. Barbara, CA). The data analysis was conducted offline by customized Matlab programs (2012b, Mathworks, Natica, MA).

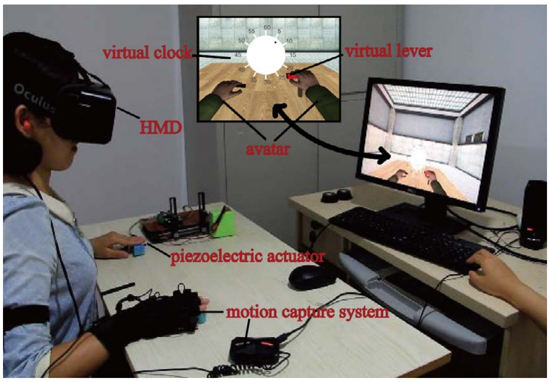

Fig. 1. Experimental setup. The participant sits in front of a desk, and the virtual environment is spatially congruent with the real environment. Their right hand is motion-tracked and left hand is stimulated by a piezoelectric actuator. The visuomotor tasks involving the avatar and the intentional binding task were performed within the virtual environment.

2.2. Participants

We recruited a total of 43 participants, ranging from 19 to 27 years old, in our main experiment. All participants were right-handed, had normal or corrected-to-normal vision without a known history of psychiatric or neurological disorders. All participants signed an informed consent form and were paid for their participation. They were randomly assigned to one of the three groups: *VR* group (8 females and 10 males, age: 23.6 ± 2.6, average ± SEM, same below), *VR control* group (10 females and 8 males, age: 22.3 ± 2.4) and *Reality control* group (5 females and 6 males, age: 22.4 ± 2.4). Four participants were included both in the *VR* group and the *Reality control* group. We also performed a control experiment by recruiting two additional groups of participants to measure their subjective SoA and SoO immediately after VR exposure. Without performing the intentional binding task, they went through the same procedures as the *VR* group (n = 13; 7 females and 6 males, age: 24.2 ± 2.4) and the *VR control* group (n = 15, 7 females and 8 males, age: 23.6 ± 2.5), respectively. Their results were included in the supplementary material. The Institutional Review Board of Peking University approved all procedures.

2.3. Procedures

For *VR* and *VR control* group, the experiment was divided into three phases: a pretest, a VR exposure phase, and a posttest. In the pretest and posttest, we measured participants' SoA when they observed their own avatar's movement. In the exposure phase, participants performed goal-directed actions in the virtual environment with (*VR* group) or without (*VR control* group) their avatar. After pretest and posttest, these two groups also completed questionnaires to measure their subjective feeling of SoO and SoA. Participants in *Reality control* group only had their SoA measured in the real environment without HMD. Thus, their performance served as a baseline.

2.3.1. Measuring SoA by an intentional binding task

The implicit SoA was quantified by the intentional binding effect with classical Libet's clock paradigm (Haggard et al., 2002). Participants were asked to put their arms on the desk with the piezoelectric disc placed underneath their left index finger. In the VR setting, they could see their avatar sitting in a spatially congruent position of their own body (Fig. 1). They could also observe a virtual piezoelectric disc underneath avatar's left index finger. Participants were asked to fixate on a virtual clock face (Fig. 1). The clock had a 1.2 cm-long hand, which rotated with a period of 2500 ms per circle. The clock face was marked with conventional "5-min" intervals. The trial started when the clock hand started to rotate from a random clock position. It ended after participants reported their timing judgment.

In the *Operant* condition, participants observed their avatar's right hand press a lever at a random time and received a vibrotactile stimulus delivered to their own left hand 250 ms later. The stimulus was a 10-ms vibration designed as a 100 Hz sine-wave with an amplitude of 0.5 mm. The clock hand would stop rotation after a random interval (between 1.5 s and 2.5 s) after the stimulus was delivered. Participants then verbally reported the position of the clock hand when they felt the stimulus. Any number between 0 and 60 was considered as a valid judgment. Participants were told not to restrict themselves to using the numbers marked on the clock face. The experimenter recorded the reported numbers. Participants familiarized themselves for this task for five trials; they were instructed that they should focus on the clock while still paying attention to their avatar's right hand. The clock was displayed at the center of the screen, extending about 7°. The two avatar hands were symmetrically displayed on two sides, extending approximately 15°. Thus, both the clock and the avatar hands were readily observed during the task. After familiarization trials, the formal data collection began with a total of 50 trials (10 practice trials and 40 test trials). After the 25th trial, they were allowed to take a one-minute rest if needed.

In the *Baseline* condition, all other procedures were kept the same except that the avatar hand remained stationary before the tactile stimulus. Participants were asked to report the timing of a randomly-presented stimulus for 50 trials. The intentional binding effect, if any, was quantified by a negative (leftward) shift of stimulus-time estimates in the *Operant* condition relative to those in the *Baseline* condition.

2.3.2. Sensorimotor exposure with the avatar in VR

We designed two motor tasks in VR. The first task was a 3D reaching task where a semi-transparent ball appeared at random locations in the avatar's reachable space (Fig. 2A). Participants were required to touch the ball as quickly as possible by using their right hand. The second task was an imitation task where participants were required to bend their fingers to follow the actions of the avatar facing them (Fig. 2B). In one of two separate sessions, the male avatar bent either one of his left-hand fingers or one of his right-hand fingers. Participants were required to bend their corresponding right-hand finger as quickly as possible. The order of these two tasks was randomized among participants. Participants could see their whole body though they just needed to move their right arm and hand to control the avatar. The total duration of these two tasks was 20 min. For the *VR* group, they could observe the avatar arm whose motion matched with the motion of the real arm continuously and simultaneously. This provided the opportunity for participants to associate their own movements to the observed movements of their avatar.

For the *VR control* group, participants went through the same procedures with the same virtual scene. However, they could not see their avatar arm. Thus, they had no direct visual experience to associate their movements with the avatar's movements.

The last group of participants (*Reality control* group) performed the intentional binding task once with their real hand and without HMD. They did not expose to the VR environment either. Their performance served as a baseline for this type of intentional binding task. We recruited this separate group of participants to prevent possible performance transfer between the intentional binding tasks

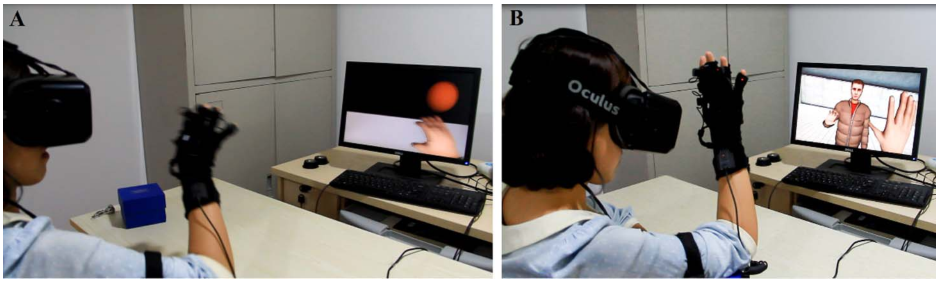

Fig. 2. Two sensorimotor tasks during VR exposure. (A) The 3D reaching task. From a first-person perspective, the participant observes a target ball appearing at a random location within the participant's reachable space. The participant reaches for the ball as quickly as possible to make it disappear. (B) The imitation task. The participant is required to bend her right fingers to mirror the action of the avatar.

performed in reality and in virtual reality.

2.3.3. Questionnaire assessing subjective feeling of SoA and SoO

For the *VR* and the *VR control* groups, we assessed their subjective feelings of SoA and SoO over the avatar immediately after the pretest and the posttest (Table 1). The questionnaire was a modified version of questionnaires used in two similar studies (Braun, Thorne, Hildebrandt, & Debener, 2014; Ma & Hommel, 2015b). It consisted of 8 items: Q1-Q3 were used to assess the strength of the subjective feeling of SoO, Q4-Q6 were to assess the SoA over the observed actions of the avatar hand, Q7-Q8 were two control questions for SoA. For each item, participants responded by choosing a score on a 7-point Likert scale, ranging from 1 for 'strongly disagree' to 7 for 'strongly agree.' The *VR* group and the *VR control* group used the same questionnaire. Due to implementation problems, we did not collect five VR participants' questionnaires and two VR control participants' questionnaires.

2.4. Data analysis

For the intentional binding task, each participant performed 40 trials for the baseline condition and the operant condition, respectively. The perceptual error of each trial was calculated as the difference between the actual timing of the vibrotactile stimulus and the reported timing. We removed extreme values (two standard deviations from the average) among the 40 trials and calculated average baseline error and operant error. The percentages of excluded trials were 0.1 ± 0.1% and 0.1 ± 0.2% for the *VR* group and the *VR control* group, respectively. The effect of intentional binding was quantified by subtracting the baseline error from the operant error. A negative value indicates that the participant perceives the tactile stimuli as occurring earlier than its actual timing. The more negative this perceptual shift, the more intentional binding. For the questionnaires, we calculated the median and interquartile range (IQR) scores for SoA, SoO, and SoA-control judgments separately.

For intentional binding effect, between-group comparisons were performed with a 2 phases (pretest and posttest) × 2 groups (*VR* group and *VR control* group) mixed-design ANOVA, and paired *t*-tests were performed for within-group comparisons when appropriate. For questionnaire results, we used Wilcoxon Signed Ranks test to perform within-group comparisons between the pretest and the posttest. We also performed the analyses without the four participants who were shared by the *VR* group and the *Reality control* group. As the results remained largely the same, we included them in the supplementary material. The significance level was set at $\alpha = 0.05$.

3. Results

In the pretest, both the *VR* group and the *VR control* group showed a negative perceptual shift, which amounted to 71.1 ± 12.2 (average ± SEM, same below) and 82.7 ± 24.0 ms, respectively (Fig. 3). This intentional binding effect was also visible in the posttest: the negative perceptual shift became 121.7 ± 11.8 and 82.8 ± 21.3 ms for the *VR* group and the *VR control* group,

Table 1
Questionnaire after the pretest and the posttest. All questions were rated on a Likert scale from 1 (strongly disagree) to 7 (strongly agree).

Category	Statement	Order of questions
SoO-judgement	1, I felt like I was looking at my own hand	1
	2, I felt like the virtual hand was part of my body	6
	3, It seemed as if my hand was pressing when I saw the movement	5
SoA-judgement	4, It seemed as if the virtual hand moved obeying my will	4
	5, It seemed as if the virtual hand pressed the button instead of me	3
	6, If I moved my finger, I felt that the virtual finger would move in the same way	7
SoA-control	7, I felt as if the movement of virtual hand had no relationship with me	8
	8, It seemed as if the virtual hand had a will on its own	2

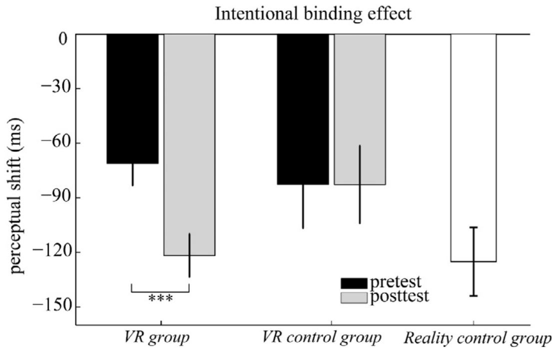

Fig. 3. Average perceptual shifts measured by the intentional binding task before and after VR exposure. The results from different groups are plotted separately. Note that the *Reality control* group was only measured once. *** stands for $p < 0.001$.

respectively. To reveal the effect introduced by VR exposure, we performed a 2 (pretest and posttest phases) × 2 (*VR* and *VR control* groups) mixed-design ANOVA on the perceptual shift. The interaction was significant ($F_{1,\ 34} = 9.0$, $p = 0.005$, Cohen's $f = 0.5$). The main effect of phase was significant ($F_{1,\ 34} = 9.08$, $p = 0.005$, Cohen's $f = 0.5$), indicating that the perceptual shift became more negative for the posttest. The main effect of group was not significant ($F_{1,\ 34} = 0.32$, $p = 0.58$, Cohen's $f = 0.02$). Simple main effect test found no difference between the pretest and the posttest for the *VR control* group ($F_{1,\ 34} = 0.00008$, $p = 0.99$, Cohen's $f = 0.000004$). More importantly, there was a significant simple main effect between the pretest and the posttest for the *VR* group ($F_{1,\ 34} = 18.08$, $p = 0.00015$, Cohen's $f = 1.0$), indicating that intentional binding was stronger after VR exposure with the avatar.

Interestingly, the size of the perceptual shift in the *VR* group was comparable to that of the *Reality control* group (-125.2 ± 25.1 ms). In fact, they were not significantly different ($t_{34} = 0.15$, $p = 0.88$, Cohen's $d = 0.21$).

We further analyzed the perceptual error in the baseline conditions and the operant conditions separately. For the *VR* group, the baseline error was 8.20 ± 12.26 and -12.28 ± 13.40 ms for the pretest and posttest, respectively. For the *VR control* group, it was 6.56 ± 12.44 and 12.91 ± 16.21 ms for the pretest and posttest, respectively. First, the baseline error did not differ from zero for all conditions and groups (*VR* group: $t_{17} = -0.67$, $p = 0.51$ and $t_{17} = 0.91$, $p = 0.37$ for the pretest and posttest, respectively; *VR control* group: $t_{17} = -0.52$, $p = 0.60$ and $t_{17} = 0.80$, $p = 0.44$ for the pretest and the posttest, respectively). Second, both groups showed marginally significant difference in baseline error between the pretest and the posttest with small effect size ($t_{17} = -2.08$, $p = 0.053$, Cohen's $d = 0.49$ and $t_{17} = -2.09$, $p = 0.051$, Cohen's $d = 0.49$, respectively). These results indicated that before and after VR exposure participants' timing judgment remained accurate when the avatar's action was absent. Third, in the operant condition, the perceptual errors were similar for the *VR group* and the *VR control* group in the pretest (-79.3 ± 18.2 ms and -89.3 ± 22.1 ms, respectively). These operant errors were much more negative than the baseline errors, suggesting that observing avatar's actions indeed induced binding effect even before active control of the avatar in VR. Furthermore, this operant error started to differ between groups in the posttest as the *VR* group exhibited more perceptual shifts (-109.5 ± 17.7 ms and -69.9 ± 20.7 ms, respectively), highlighting the effect of controlling a visible avatar.

To reveal whether the binding effect changed within an intentional binding session, we computed the average perceptual shifts for the first half and the second half of trials in the operant condition separately (Fig. 4). Between the first half and the second half of each phase, this perceptual shift did not differ for each group of participants (*VR* group: $t_{17} = -0.40$, $p = 0.70$ and $t_{17} = -0.97$,

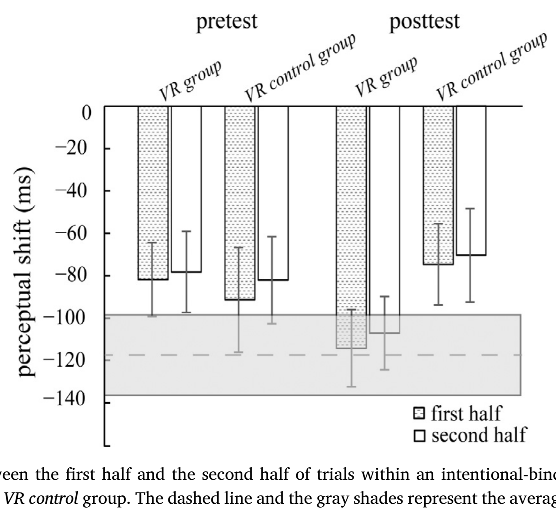

Fig. 4. Comparison of perceptual shifts between the first half and the second half of trials within an intentional-binding session. The pretest and the posttest are presented separately for the *VR* group and the *VR control* group. The dashed line and the gray shades represent the average ± SEM of the perceptual shift in the *Reality control* group.

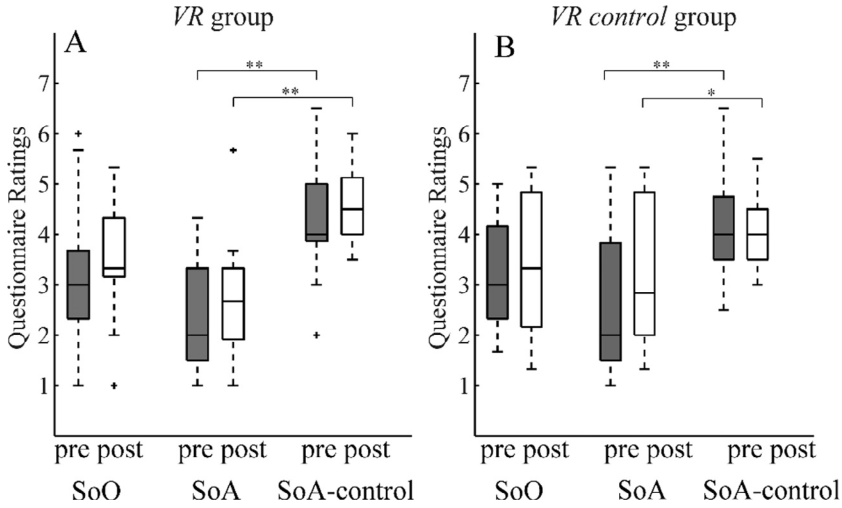

Fig. 5. Boxplots for the questionnaire results of the pretest and the posttest. (A) SoO, SoA, SoA-control scores for the *VR* group. (B) The SoO, SoA, SoA-control scores for the *VR control* group. For both graphs, the horizontal bars are the medians, and the boxes are the interquartile ranges (IQRs). The whiskers stretch to the data points that are within the median ± 1.5 IQR, with outliers beyond this shown as single points. No significant difference between the pretest and the posttest is found.

$p = 0.34$ for the pretest and posttest, respectively; *VR control* group: $t_{17} = -0.62$, $p = 0.54$ and $t_{17} = -0.85$, $p = 0.41$, respectively). Thus, the binding effect is unlikely a result of learning over the trials within each operant condition.

To examine whether the subjective feeling of SoA and SoO differed at the times of measurement of intentional binding, we made comparisons between the two questionnaire results obtained immediately after the pretest and after the posttest (Fig. 5). For both groups, the perceived SoO and SoA did not differ between the pretest and the posttest (z = −0.16, $p = 0.86$ and z = −0.72, $p = 0.47$ for SoO in *VR* participants and *VR control* participants, respectively; z = −0.42, $p = 0.67$ and z = −1.06, $p = 0.29$ for SoA in *VR* participants and *VR control* participants, respectively). These results indicate that explicit reports of SoO and SoA did not differ between the pretest and the posttest though the implicit measure of SoA differed. For both the pretest and the posttest, the average scores of SoA-control were significantly higher than those of SoA (pretest: $z = -2.77$, $p = 0.006$ for the *VR group*, $z = -2.81$, $p = 0.005$ for the *VR control* group; posttest: $z = -2.90$, $p = 0.004$ for the *VR* group, $z = -1.94$, $p = 0.049$ for the *VR control* group), indicating that participants correctly understood our instructions and successfully completed this explicit-report task.

Overall, the questionnaire scores were relatively low as compared to findings in similar studies (Kokkinara et al., 2016; Ma & Hommel, 2015b). We postulated that this was because our questionnaires were administrated after the intentional binding task instead of immediately after the VR exposure. Thus, we performed a control experiment by recruiting another two groups of participants who went through the same VR experience as the original *VR* and *VR control* groups. However, they immediately answered questionnaires without further testing of intentional binding. The results confirmed our hypothesis: the scores in SoO and SoA were comparably high as in the literature. These results were detailed in the supplementary material.

4. Discussion

The aim of our study is to investigate whether movement experience in an immersive VR environment can change the experienced SoA. We are particularly interested in examining whether mere observation of the action of an avatar can elicit implicit SoA. We used the intentional binding paradigm to measure the SoA before and after performing goal-directed actions with an avatar in VR. First, we found that intentional binding was already present in the pretest when minimum VR experience was given for both *VR* and *VR control* groups. Second, the binding effect became significantly stronger in the posttest for the *VR* group but not for the *VR control* group. Interestingly, the binding effect size in the *VR* group was comparable to that of the *Reality control* group who performed the intentional binding task in the real environment without VR headset. Third, we found dissociation between the implicit measure of SoA (intentional binding) and the explicit measure of SoA (questionnaire) for the avatar: while implicit SoA measures were affected by VR exposure, participants' explicit reports of SoA and SoO did not change at the time when implicit measures were taken. Hence, our findings suggest that a short period of active engagement in immersive VR can elicit implicit attribution of SoA to a virtual representation of the actor.

Whether observing an action executed by a third party can elicit temporal binding effect or not has been previously investigated. In early studies of intentional binding, the shortening of action-to-outcome duration has been consistently found if we compare the estimated duration between a voluntary condition and an involuntary condition where the movement is induced by TMS (Haggard & Clark, 2003; Haggard et al., 2002) or passive movement (Engbert, Wohlschlager, & Haggard, 2008). Researchers have emphasized the necessity of intentionality, predictive motor control and motor planning for inducing the binding effect (Frith, 2005; Haggard et al., 2002; Hughes, Desantis, & Waszak, 2013; Stetson, Cui, Montague, & Eagleman, 2006). However, later studies have found that an action performed by a third party also leads to binding. For example, binding occurs when the action is executed by other people (Poonian & Cunnington, 2013; Wohlschläger, Haggard, Gesierich, & Prinz, 2003) or even by a machine (Buehner, 2012).

Nevertheless, several studies reported an absence of the binding effect when the action outcome was caused by a non-agent such as a computer or a machine (Obhi & Hall, 2011; Wohlschläger et al., 2003). It has been proposed that whether the third party is regarded as causally producing the outcome, in a way like an agent, is a critical factor for inducing the effect. For instance, regarding the absence of binding in early studies where actions were performed by a machine (Wohlschläger, Engbert, & Haggard, 2003; Wohlschläger et al., 2003), Buehner argued that these early studies used a single computer to control the machine action and to play the tone outcome. Thus, there was no obvious causal relationship between the machine action and the tone, which resulted in a lack of binding effect. Buehner designed his series of experiments with a clever modification: a standalone machine (without apparent connection to a computer) pressed the lever and also appeared to autonomously trigger the tone (Buehner, 2012). This machine condition then succeeded in inducing temporal binding effect, highlighting that causality or a (seeming) agent is necessary for binding effect. Interestingly, these insights echo with the function of mirror systems which involve dedicated neural circuits that are activated during self-generated action as well as during observation of others' action (see a review, Rizzolatti & Sinigaglia, 2010). Mirror systems similarly do not show activity when the observed action is carried out by a non-agent. Our findings are consistent with the previously reported binding effect associated with an observed agent: as a third party, the avatar in our VR setting elicits the intentional binding effect. This might suggest that our participants treat the avatar as an agent whose movements causally relate to the tactile stimulus delivered to their hand.

It is intriguing that the binding effect (a temporal shift of ~80 ms) was evident as early as in the first half of the pretest when the experience of controlling the avatar was still minimal. Based on previous studies, causal relationship between the movement (of the avatar) and the subsequent tactile stimulus is sufficient to produce a binding effect (Buehner, 2012; Wegner, 2003). Thus, binding is expected if participants learn the causal relationship by the repetitive pairing of action and outcome during the pretest. However, a substantial binding effect manifested itself in the first half of the pretest, strongly suggesting that SoA was already misattributed to the avatar at this early stage. We speculate that embodiment, brought by a spatially matched avatar in immersive VR environment, underlies this immediate effect. People have previously found that sense of bodily ownership and sense of agency are largely unrelated given double dissociation between them in behavioral studies (Braun et al., 2014; Imaizumi & Asai, 2015; Kalckert & Ehrsson, 2012; Longo, Schuur, Kammers, Tsakiris, & Haggard, 2008; Sato & Yasuda, 2005; Manos Tsakiris, Prabhu, & Haggard, 2006) and distinct neural circuits associated with them (Tsakiris, 2010; Tsakiris, Schutz-Bosbach, & Gallagher, 2007). However, this double association between SoO and SoA does not mean that they are independent. For example, when rubber hand illusion is successfully induced, or SoO is high, higher SoO is associated with higher SoA as reflected by significant correlations between their subjective ratings (Braun et al., 2014; Kalckert & Ehrsson, 2012, 2014). Furthermore, a rubber-hand illusion study found that when the robotic hand was placed in an incongruent position to the actual hand, the intentional binding effect associated with its actions was reduced, suggesting that reduced embodiment leads to smaller binding effect (Caspar, Cleeremans, & Haggard, 2015). Similarly, it was found that after experiencing synchronous avatar actions in immersive VR people biased their utterance frequency towards that of the avatar (Banakou & Slater, 2014). The authors also proposed that bodily ownership over the avatar led to this observed agency effect. Thus, there is converging evidence that SoO and SoA are correlated. The immediate binding effect in the present study lends further supports that embodiment enhances SoA. When participants performed the Libet clock task for the first time in the pretest, they placed both hands on the desk where the avatar hands were spatially overlaid. Immersion in this virtual environment with a first-person perspective and with an avatar body of morphological similarity potentially creates a strong embodiment effect even before any active movements. Thus, embodiment biased the temporal judgment of the tactile stimulus when the avatar hand moved.

Our major finding is that after controlling an avatar in VR for a brief period, the *VR* group developed more intentional binding. In fact, the temporal shift became as large as in the *Reality control* group who performed the same intentional binding task with their real hand without VR headset. This effect and its effect size strongly support that VR experience enables an enhanced sense of agency to the avatar. Critically, this VR exposure effect was absent in the *VR control* group where participants performed the same goal-directed tasks in VR without seeing the avatar. Thus, the effect was not caused by confounding factors such as mere immersion in a VR environment or repeated tests of intentional binding (Stetson et al., 2006). It also suggests that sensorimotor experience with a visible avatar is critical for inducing misattribution of agency to an avatar. Desantis and colleagues recently reported that intentional binding was stronger when participants believed the actions were self-made as opposed to made by another person (Desantis, Roussel, & Waszak, 2011). In this light, our findings suggest that people tend to attribute the avatar hand's action to themselves after controlling the avatar hand for a brief period.

It is noteworthy that in our study the measurement of SoA and the VR exposure were realized by two completely different tasks, the former being a temporal judgment task with a static posture and the latter two goal-directed tasks with arm movements. This is fundamentally different from the study conducted by Banakou and Slater (2014). In their experiments, the VR exposure was to let participants observing and hearing the talking of an avatar. The SoA effect was a biasing effect of fundamental frequency of participants' utterance. Thus, their VR exposure involved observation of the same task as for the measurement of SoA, i.e., speaking. This, arguably, gives room for alternative explanations for their VR effect such as carryover effect of automatic mimicry, as postulated by the authors of that paper. Our experiment instead observed (mis-)attribution of agency across tasks and thus provided strong support for VR exposure effect.

Another possible factor contributing to increased binding is that VR experience might further enhance embodiment. People have found that immersive VR is efficient in changing SoO (Kilteni et al., 2012; Perez-Marcos et al., 2012; Petkova & Ehrsson, 2008; Slater et al., 2008, 2009; Suzuki et al., 2013; Tieri et al., 2015). For instance, the mere observation of avatar discontinuity in immersive VR affects perceived ownership (Tieri et al., 2015). However, our questionnaire data indicated that explicit judgment of SoO did not increase after VR exposure. In fact, the questionnaire results did not find an increase in SoA scores either. Thus, we observed a dissociation between the explicit agency and implicit agency: on the one hand, VR experience led to a stronger binding effect; on the other hand, subjective feeling of controlling the avatar remained the same. This finding is consistent with a growing literature that sense of agency has two separate aspects, one is at the implicit and non-conceptual level that does not involve explicit agency attribution, the other is at the explicit and conceptual level where judgment of being an agent emerges (Moore, Middleton, Haggard, & Fletcher, 2012; Synofzik, Vosgerau, & Newen, 2008). The implicit and explicit measures of SoA could be uncorrelated (Braun et al., 2014; Dewey & Knoblich, 2014; Ebert & Wegner, 2010; Saito, Takahata, Murai, & Takahashi, 2015), as supported by our findings.

The SoO scores in our experiments were lower than those reported previously. A possible reason is that our questionnaires were administrated after the pretest and posttest, while other studies accessed senses of ownership and agency immediately after VR exposure. The median score of *VR* group we measured was 3.0 (pretest) and 3.3 (posttest) while people have reported a score at about five after VR exposure with a similar questionnaire (Kokkinara et al., 2016; Ma & Hommel, 2015b). During our pretest and posttest, participants performed the intentional binding task when they did not move their hand but rather passively observed the movement of the avatar hand. This created asynchrony or mismatch between actual body state and virtual body state. Previous studies have shown that asynchrony between real movements and rubber-hand movements weakens both ownership and agency (Kalckert & Ehrsson, 2012; Tsakiris, Longo, & Haggard, 2010). Thus, we postulate that the experience during the pretest and posttest might reduce the feeling of ownership and agency that was built up during VR exposure, resulting in lower scores than previously reported. This explanation was supported by our control experiment in which modified questionnaires were administered immediately after VR exposure. Both SoA and SoO scores were similarly high as in previous studies.

Our findings indicate that sensorimotor experience in VR contributes to the misattribution of agency to an avatar. Other studies have manipulated beliefs about agency and also successfully induced changes in agency attribution (Aarts, Custers, & Wegner, 2005; Desantis, Weiss, Schütz-Bosbach, & Waszak, 2012; Desantis et al., 2011; Dijksterhuis, Preston, Wegner, & Aarts, 2008; Dogge, Schaap, Custers, Wegner, & Aarts, 2012; Olson, Landry, Appourchaux, & Raz, 2016). For instance, Dijksterhuis et al. found that subliminally priming prior thought to an action affected people's attribution of authorship for that action. Participants reported greater feelings of authorship when primed with first person singular pronouns, and lower feelings of authorship when primed with a "computer." Moreover, when participants were primed with God their authorship attribution was also affected, but the effect was limited to those who believed (Dijksterhuis et al., 2008). More recently, Olson et al. demonstrated that participants felt less control over their choice when they were convinced that a machine could influence their thoughts (Olson et al., 2016). Thus, agency attribution can be modified both by top-down and bottom-up influences; the latter influence can come from the sensorimotor experience in VR as shown in the present study.

Our findings could not be explained by divided attention during the intentional binding tests in our VR setup. To fulfill the task, participants were required to focus on the virtual clock face and simultaneously observe the motion of the avatar hand. If participants attended less to the clock face in the operant condition when the avatar hand moved, we should observe a delayed timing estimate of the tactile stimulus as compared to the performance in the baseline condition where the avatar hand remained stationary. On the contrary, we observed a negative shift of timing estimate in both the pretest and posttest among all participant groups, opposite to the prediction of divided attention. Also, previous studies on intentional binding also used the Libet clock together with other visual stimuli (Desantis et al., 2011; Engbert & Wohlschlager, 2007; Moretto, Walsh, & Haggard, 2011; Vinding, Jensen, & Overgaard, 2015). For instance, a recent study investigating the effect of moral contexts on intentional binding presented participants a story-telling picture on top of the Libet's clock (Moretto et al., 2011). None of these studies reported any influence of divided attention.

Two recent electroencephalography studies examining neural signatures associated with movement errors committed by the avatar in VR were particularly relevant to our study (Padrao, Gonzalez-Franco, Sanchez-Vives, Slater, & Rodriguez-Fornells, 2016; Pavone et al., 2016). Pavone and colleagues found that observation of erroneous actions performed by an avatar elicited specific brain activities that are traditionally associated with early and probably automatic detection of self-committed errors (Pavone et al., 2016). Importantly, this effect was enhanced when the embodiment was high and when the participants viewed the avatar action in the first-person perspective. Thus, embodiment induced by immersive VR indeed affects the neural processing of observed movement errors by an avatar. Interestingly, event-related brain potentials (ERP) associated with late conscious awareness of the errors were comparable across trials with different levels of embodiment, suggesting that these late brain activities might represent a disembodied coding of errors in both self and others. In the second study involving avatar actions in VR, Padrao and colleagues found that avatar-committed false movement errors, when accompanied with participants' actual movements, elicited late ERP signatures that were similar to semantic or conceptual violations (Padrao et al., 2016). These agency violation-related signals were absent if the participants merely observed the avatar making the false movement errors without their own movements. The discrepancy between these two studies might stem from the fact that the participants only passively observed the avatar's actions in the first study while the participants also actively moved when observing the avatar's actions in the second study. It would be interesting to combine ERP techniques with our paradigm to investigate the neural signatures of avatar-induced SoA. In fact, our paradigm closely resembles Pavone et al.'s since our participants also merely observed the avatar's actions without self-movements during the intentional binding task. In our study, the avatar's action should not be viewed as a movement error per se, but it creates reliable perceptual shifts that are traditionally associated with SoA.

5. Conclusion

Our study suggests that an avatar in immersive VR can elicit implicit SoA in its owner. Before sensorimotor experience with the avatar, this effect is already present even though initially small, possibly due to an immediate embodiment. The effect further increases after people control the avatar in VR for a brief period, suggesting that VR experience contributes to the development of an operant relationship between action and its outcome. As quantified by intentional binding effect, the level of SoA elicited by the avatar is comparable to that of real human actions outside of VR. This implicit agency effect is accompanied by a lack of change in subjective reports of SoA and SoO, suggesting that VR experience effectively operates on the pre-conscious level. Hence, immersion in virtual reality influences not only our attitude and self-perception but also fundamental aspects of our self-consciousness. This should be taken into consideration as the boundary between reality and virtual reality becomes increasingly obscure in our society.

Authors' contribution

KW developed the study concept. GK and KW designed the study. The experimental setup was prepared by GK and KH. Data collection was performed by GK. GK performed the data analysis and interpretation under the supervision of KW. GK and KW wrote and revised the manuscript. All authors approved the final version of the manuscript for submission.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.concog.2017.04.018.

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