Virtual Reality (2024) 28:1
https://doi.org/10.1007/s10055-023-00907-8

ORIGINAL ARTICLE

The distinction between first-person perspective and third-person perspective in virtual bodily self-consciousness

Wei-Kai Liou[1] · Wen-Hsiang Lin[2] · Yen-Tung Lee[3,4] · Sufen Chen[2,5] · Caleb Liang[6,7]

Received: 15 February 2023 / Accepted: 1 November 2023 / Published online: 23 December 2023
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2023

Abstract

The distinction between the first-person perspective (1PP) and the third-person perspective (3PP) has been widely regarded as fundamental and rigid, and many researchers hold that genuine bodily illusions can only be experienced from the 1PP. We applied VR technology to investigate whether this mainstream view is correct. In our experiments, the participants were immersed in a VR environment in which they saw a life-sized virtual body either from the 1PP or from the 3PP. They either passively received tactile stimulations and/or actively interacted with a virtual soccer ball. Our VR system created novel visuo-motor-tactile correlations between the real and the virtual world: when the participant interacted with a real plastic soccer ball, he/she would feel corresponding tactile sensations and see the avatar performing the exact same movements. We found that a clear sense of ownership over the avatar was induced not only in the 1PP condition but also in the Passive-3PP and the Active-3PP conditions. We also observed evidence suggesting that it is possible to experience one's body-location, 1PP-location, as well as self-location, both from the 1PP and from the 3PP. Together, we demonstrate that there is in fact no fundamental gap between embodied 1PP and embodied 3PP in the virtual world.

Keywords First-person perspective · Body ownership · Self-location · Body-location · 1PP-location · Virtual reality

1 Introduction

1.1 Target issue and motivation

One of the major insights in the contemporary philosophy of mind is that each conscious self is uniquely associated with a first-person perspective (1PP), and correlatively, that all conscious experiences are essentially anchored in a particular 1PP (Husserl 1973; Wittgenstein 1958; Nagel 1974; Baker 2000; Levine 2001; Zahavi 2005, 2020). This insight is supported and articulated by interdisciplinary studies (Metzinger 2003; Legrand 2007; Gallagher 2000, 2012; Blanke and Metzinger 2009; Liang 2016), including neuroscientific works (Legrand and Ruby 2009; Christoff et al. 2011; Blanke 2012). Specific neural correlates of 1PP have also been suggested (Vogeley and Fink 2003; Vogeley et al. 2004; David et al. 2006; Ionta et al. 2011; Serino et al. 2013). The most basic and common way to characterize 1PP is to contrast it with the third-person perspective (3PP): (1) *Origin*: 1PP is the origin of the egocentric spatial framework that structures one's perceptual experiences and bodily movements. I perceive and interact with the world from my 1PP. Wherever I go, my 1PP is

✉ Caleb Liang
yiliang@ntu.edu.tw

1 Empower Vocational Education Research Center, National Taiwan University of Science and Technology, Taipei, Taiwan

2 Graduate Institute of Digital Learning and Education, National Taiwan University of Science and Technology, Taipei, Taiwan

3 Department of Philosophy, Western University, London, Canada

4 Rotman Institute of Philosophy, Western University, London, Canada

5 Optentia Research Focus Area, North-West University, Vanderbijlpark, South Africa

6 Department of Philosophy, National Taiwan University, Taipei, Taiwan

7 Graduate Institute of Brain and Mind Sciences, National Taiwan University, Taipei, Taiwan

always "here" with me since it is my 1PP that defines and underlies what I feel as "here". (2) *Exclusiveness*: the 1PP that I have is no one else's but mine. Your 1PP is a 3PP to me. Other subjects can only observe me undergoing my experiences from the 3PP. (3) *Interiority*: 1PP can be experienced "from the inside" by the subject. Consider vision: I see things with my eyes, but I do not thereby see my eyes. Still, due to proprioceptive information from extraocular muscles, I can be implicitly aware of both the location and the orientation of my visual perspective "from the inside", even though it is often "attentively recessive", i.e., I usually focus on what I see rather than on the spatial properties of my visual perspective. The point is that our conscious experiences are permeated with these distinctive features of 1PP, and 3PP has none of them.

Due to these observations, most researchers assume that the distinction between 1PP and 3PP is rigid such that experiences based on 1PP are *fundamentally different* from experiences based on 3PP. This assumption has become a mainstream view in the study of bodily self-consciousness (Zahavi 2005; Legrand 2007; Petkova et al. 2011; Gallagher 2012; Maselli and Slater 2013). For example, Petkova et al. (2011) argued that "the first person visual perspective would represent a fundamental constraint on the full-body illusion." They further said that "the first person visual perspective is critical for triggering the illusion of full-body ownership. This is an important observation as it shows that the very basic sensation of owning one's body is the result of a constructive process where visual, tactile, and proprioceptive signals are integrated in ego-centric coordinates." A key question arises: Is this mainstream view correct? In this study, we suppose that the philosophical observations mentioned earlier are plausible. The question that we want to pursue is: Must it be implied that there is a fundamental chasm between 1PP-experience and 3PP-experience?

The current study is motivated by the thought that the relationship between 1 and 3PP may be more complicated than the mainstream view. Why? Because 1PP and 3PP share one feature that is equally essential: (4) *Embodiment*: my 1PP is not an abstract geometric point; rather, it is anchored on my body. Likewise, your 1PP, as a 3PP to me, is anchored on your body. Since both 1PP and 3PP are embodied, they have spatial properties such as location and orientation. The location and orientation of one's body has great influences on these spatial properties, and one's experiences, of the 1PP. It is this feature of Embodiment that makes empirical studies of 1PP and 3PP possible. So, the question now becomes: given the features of Origin, Exclusiveness, Interiority and Embodiment, are experiences based on 1PP and experiences based on 3PP fundamentally different? Or is the difference between them a matter of degree? In this study, we applied VR technology to investigate this issue. Below, we sharpen this issue by focusing on two central topics in the study of bodily self-consciousness: *body ownership* and *self-location*.

1.2 Body ownership and self-location

As a key component of bodily self-consciousness, body ownership concerns whether a body-part or a full body is experienced *as one's own*. Many researchers consider the distinction between 1PP and 3PP to be so crucial that, in order to induce the rubber hand illusion or full body illusions, the fake hand or the virtual body must be viewed from the 1PP (Tsakiris and Haggard 2005; Petkova and Ehrsson 2008; Petkova et al. 2011; Maselli and Slater 2013). This generates a live issue: can genuine illusions of body ownership be induced by a 3PP set-up where the body-part or the full body is viewed from the 3PP? In the study by Lenggenhager et al. (2007), participants received tactile stimulations on the back while watching from the 3PP a virtual body standing in front being stroked. The questionnaire results showed that many subjects felt as if the virtual body was their own (see also Lenggenhager et al. 2009). Drawing on crossmodal congruency effects (CCEs), Aspell et al. (2009) reported similar results by using a different 3PP set-up (see also Aspell et al. 2013; Heydrich et al. 2013). In contrast, the studies by Petkova et al. (2011) and Maselli and Slater (2013) argued for a negative answer. For example, Petkova et al. (2011) contended that, since watching the virtual body from the 3PP was similar to recognizing oneself on a monitor, it could be just a case of visual self-recognition "without necessarily experiencing a somatic illusion of ownership". Thus, the authors claimed that watching the virtual body from the 1PP was absolutely essential for illusions of body ownership to occur (see also Ehrsson 2007; Petkova and Ehrsson 2008; Slater et al. 2010; Guterstam and Ehrsson 2012; Bergström et al. 2016; Maselli and Slater 2013; Kokkinara et al. 2016). However, if the answer turns out to be yes, i.e. if illusory body ownership can genuinely be experienced from the 3PP, that would support the view that the distinction between embodied 1PP and embodied 3PP is actually not rigid but a matter of degree. If so, the mainstream view mentioned above will be seriously challenged. We aimed to investigate this issue by conducting new VR experiments.

In addition to body ownership, self-location has been considered as another key component of bodily self-consciousness (Blanke and Metzinger 2009; Blanke 2012; Serino et al. 2013). It refers to the subjective feeling of *where I am* in space. It is worth noting that self-location is closely related to two other types of spatial awareness: *body-location* (the sense of *where my body is located* in space), and *1PP-location* (the sense of *where my 1PP is located* in space) (see below). In daily life, these types of spatial awareness match each other and are experienced from the 1PP, that is, one's senses of self-location and body-location match each other and overlap with one's sense

of 1PP-location. To make the notion of self-location experimentally operational, many previous studies simply assumed that self-location is identical to body-location or at least did not distinguish between the two (Serino et al. 2013; Maselli and Slater 2014; Guterstam et al. 2015). However, not all researchers subscribe to this assumption. For example, in Lenggenhager et al. (2007), while most subjects did not feel that their real body was drifting towards the front (questionnaire result), they did mislocalize themselves outside their real body and towards the virtual body (measurement of drift in self-location; see also Aspell et al. 2009). In another study, Aspell et al. (2013) used cardio-visual stimulations to induce similar drift. In Lenggenhager et al. (2009), illusory self-location was observed by using the mental ball dropping task (MBD) (see also Ionta et al. 2011). Moreover, it is doubtful whether self-location and body-location are really the same. In the case of out-of-body experience (OBE), subjects ''seem to be awake and feel that their 'self', or center of awareness, is located outside of the physical body and somewhat elevated. It is from this elevated extrapersonal location that the subjects experience seeing their body and the world'' (Blanke and Mohr 2005). This suggests that it is possible for one's sense of self-location to be dissociated from one's sense of body-location, and that the sense of 1PP-location might contribute to the sense of self-location. Thus, in this study, we do not assume that self-location, body-location and 1PP-location are the same phenomena (Huang et al. 2017). We intend to examine the distinction between embodied 1PP and embodied 3PP in relation to each of them.

A few clarifications before we proceed: (i) in this study, self-location, body-location and 1PP-location refer to *subjective experiences* rather than the physical locations of the real body or eyes. (ii) To make the notions of 1PP and 3PP experimentally operational, we will focus on the visual sense of these notions. Yet, we are aware that proprioceptive, vestibular and tactile information, etc., also contribute to one's egocentric reference frame. (iii) We followed most previous studies of full-body illusions in specifying the distinction between 1PP-experience and 3PP-experience (Petkova et al. 2011). 1PP-experience refers to the experience of viewing an illusory body from the 1PP as if one directly looks down at one's own body. 3PP-experience refers to the experience of viewing an illusory body from the 3PP as if one looks at someone else's body from a distance. (iv) We think that the most relevant feature of 1PP in relation to bodily experience is its location and orientation. For brevity, we will call it 1PP-location.

2 Study design

In this study, we applied VR technology to investigate the relationship between embodied 1PP and embodied 3PP. As we will see later, we defined two specific points of space to represent the position of 1PP (called Zero Point) and the position of 3PP (called Avatar Position) in the virtual environment of our experiments. We intended to address the following issues: Can full-body ownership be experienced not only from the 1PP but also from the 3PP? Could one's sense of self-location drift from Zero Point toward the Avatar Position during manipulations? Is it possible to experience one's body-location and/or one's 1PP-location not only at Zero Point but also at the Avatar Position?

In our experiments, the participant wore a head-mounted display (HMD) and was immersed in a VR environment. We used a life-sized avatar that wore an orange jacket, and the participant also wore an orange jacket. Such a design was compatible with the general idea of the Proteus Effect (Yee and Bailenson 2007), and hence could potentially enhance the likelihood of inducing the relevant 3PP bodily experiences. In the Passive 1PP conditions, the participant saw the avatar from the 1PP and passively received tactile stimulations. In the Passive 3PP conditions, the participant saw the avatar from the 3PP, standing on the right-front side about 45° and about 45 cm away, and passively received tactile stimulations. The idea of this 3PP set-up was to create a kind of spatial misalignment between the avatar and the participant (Gonzalez-Franco et al. 2020), and to see whether the relevant 3PP-experiences might be induced when suitable feedback and calibration are available (Ebrahimi et al. 2018; Day et al. 2019). In the Active 3PP conditions, the participant again saw the avatar from the 3PP, standing on the right-front side about 45° and about 45 cm away, and received tactile stimulations, and then the participant actively interacted with a virtual soccer ball. The most innovative part of the VR technology in this study was that we created novel visuo-motor-tactile correlations between the real and the virtual worlds. When the participants interacted with a real plastic soccer ball, they would feel corresponding tactile sensations on their body and at the same time see a life-sized avatar exhibiting the same postures and performing the exact same movements, using the corresponding virtual limbs to interact with a virtual soccer ball (see §3.5 for more details). Such visuo-motor-tactile correlations, we suspect, would modulate the participant's subjective experiences of full body ownership, self-location, body-location and 1PP-location.

We tested the following hypotheses: (1) the illusory experience of full-body ownership can be induced both from the 1PP and from the 3PP. (2) Under manipulations, the participant's sense of self-location can exhibit drift toward the 3PP position, i.e. the Avatar Position. As mentioned above, there have been some previous studies that supported these two hypotheses (Lenggenhager et al. 2007, 2009; Aspell et al. 2009, 2013; see also Palluel et al. 2011, 2012). (3) It is possible for the participants to experience their body-location and/or 1PP-location at the Avatar Position as well as at the

Zero Point. If all these hypotheses are confirmed, they would raise doubts about the mainstream view mentioned earlier. Rather, the major forms of bodily self-consciousness studied here might not be absolutely constrained by the 1PP. Instead, they can also be experienced from, and hence anchored on, a 3PP. Together, these hypotheses would provide substantial support for the view that there is in fact no fundamental gap between embodied 1PP and embodied 3PP in the virtual world. If so, this would open up some new research directions in the study of bodily experiences and virtual reality.

Totally we conducted five experiments (Table 1). Each of them consisted of two conditions: synchronous and asynchronous. Data were collected by questionnaire (Table 2, see §3.8), skin conductance response (SCR), and participants' responses to the Mental Imagery Task (MIT) and the Color Ball Task (CBT) (see below. More details are provided in the Materials and Methods section.

The questionnaire was administered in Experiments 1, 2 and 4. In Experiments 2 and 4, the participants did MIT and CBT before and after the main tactile/agentive manipulations, reporting *when* a rolling ball (MIT) or *which* among a series of color balls (CBT) were felt to be closest to them. Finally, SCR has generally been regarded as reliable evidence of body ownership experience. Following the previous literature (Ehrsson 2007; Guterstam et al. 2011), we measured SCR in Experiments 1, 3 and 5.

The ideas behind our experiments are as follows. Experiment 1 consisted of passive 1PP conditions. Since 1PP has been widely considered as a crucial constraint for inducing full-body illusions (Ehrsson 2007; Petkova et al. 2011; Guterstam and Ehrsson 2012), Experiment 1 served as a basis for later comparisons. Experiments 2 ~ 5 were designed to verify in different ways whether our hypotheses mentioned above were confirmed. These experiments were partly inspired by previous literature showing that bodily illusions can be induced under passive or active manipulations (Botvinick and Cohen 1998; Tsakiris et al. 2006; Lenggenhager et al. 2007; Ehrsson 2007; Petkova and Ehrsson 2008; Kalckert and Ehrsson 2012). Thus, while Experiments 2 and 3 were passive 3PP conditions, Experiments 4 and 5 were active 3PP conditions. Also, in order to avoid a potential confounding effect, and to follow previous studies (Petkova and Ehrsson 2008; Petkova et al. 2011; Guterstam and Ehrsson 2012), we measured SCR in separate experiments. Hence, we split between Experiments 2 and 3, and between Experiments 4 and 5.

Finally, Synchronicity (sync. vs. async.) was an independent variable in each within-experiment analysis. There were

Table 1 Overview of experiments

Experiments	Variables			Measurements	Participants (n)
	Perspective	Activity	Synchronicity		
Exp. 1	1PP	Passive	Sync. v. Async	Questionnaire & SCR	n = 20 (♂14)
Exp. 2	3PP	Passive	Sync. v. Async	Questionnaire, MIT & CBT	n = 20 (♂12)
Exp. 3	3PP	Passive	Sync. v. Async	SCR	n = 20 (♂14)
Exp. 4	3PP	Active	Sync. v. Async	Questionnaire, MIT & CBT	n = 20 (♂12)
Exp. 5	3PP	Active	Sync. v. Async	SCR	n = 20 (♂8)

Table 2 Questionnaire

Body ownership	Body ownership	**Q1**	It felt as if the virtual body was my body
		Q2	It felt as if I was looking at my body
	Touch-referral	**Q3**	The touches that I felt seem to be located on the virtual body
	Agency	**Q4**	It felt as if I could control the virtual body
		Q5	It felt as if that the movements of the virtual body were my movements
Body-location	Avatar position	**Q6**	It felt as if my body was located at the place of the virtual body
	Zero point	**Q7**	It felt as if my body was located beside the virtual body
	Avatar position	**Q8**	It felt as if my body was located within the red circle
	Zero point	**Q9**	It felt as if my body was located within the blue circle
1PP-location	Avatar position	**Q10**	It felt as if my visual perspective was located at the place of the virtual body
	Zero point	**Q11**	It felt as if my visual perspective was located beside the virtual body
	Avatar position	**Q12**	It felt as if my visual perspective was located within the red circle
	Zero point	**Q13**	It felt as if my visual perspective was located within the blue circle
Double body-location		**Q14**	It felt as if my body was located at two places at the same time
Control question		**Q15**	It felt as if my body gradually became a flower

also cross-experiment comparisons. For the comparisons between Experiments 1 and 2, the independent variables were Perspective (1PP vs. 3PP) and Synchronicity. Activity (passive vs. active) and Synchronicity were the independent variables in the comparisons between Experiments 2 and 4 and between Experiments 3 and 5.

3 Materials and methods

3.1 Participants

Using G*Power v. 3.1.9.6., we carried out the power analysis to detect effects greater than partial $\eta^2 = 0.06$ (Cohen 1969/1988). To reach the power effect of 0.8, the standard value of psychological studies, each experiment should include more than 17 participants. In this study, we recruited 100 volunteers for a total of five experiments (Table 1). Each experiment involved a different group of 20 participants. All five experiments were within-subject designed, and each consisted of two conditions: synchronous and asynchronous. Every subject participated in both conditions. All participants were aged between 20 and 26 years old. Informed consent to participate was acquired from all participants. Those persons shown in the figures gave their written informed consent to publish. All experiments were conducted in accordance with the Declaration of Helsinki. This study was performed in accordance with the regulations of, and was approved by the Research Ethics Committee of National Taiwan University (NTU-REC: 202012HM035).

3.2 Equipment and software

In this study, a head-mounted display (HMD) (HTC VIVE PRO STARTER KIT/per eye 1440*1600 image resolution, wide 110° field of view, and an ultra-smooth 90 Hz refresh rate) was used to display a virtual scene. Two virtual bodies, one male and one female, were constructed using 3ds Max, Unity game engine software and VR SDK. Seven VR trackers (VIVE Tracker (2.0)/Indicator: IR LED) were used in the experiments to capture the participant's full-body movements. In order to achieve realistic visual effects, we used 3ds Max for modeling, texturing, and meshing models. We also used the rendering effects as well as the dynamic lighting effects of Unity software in designing the virtual environment. The avatar and the environment were programmed according to 1:1 equal size ratio between the virtual world and the real world.

3.3 Experimental setup

Before the experiments started, the participant was instructed to put on an orange jacket, and then wore an HMD that enabled them to look in any direction within the virtual environment. During the experiments, participants listened to white noise via the HMD. The participants wore seven VR motion trackers at various skeletal joints of their body, including two in both hands, two at both upper arms near the elbow, two at both ankles, and one in the back waist position (Figs. 1A, 2A and C, 5A and C). These motion trackers mapped the participant's full-body movements from the real world onto the VR environment in real time with pinpoint accuracy. The avatar was programmed so that it could move synchronously with the person's real body movements. This helped to recreate real-life movements in the VR environment.

In the virtual environment that we programmed, two specific points of space—Zero Point and Avatar Position—were defined as follows: first, Zero Point referred to the position in the virtual world that corresponded to the position of the participant's HMD in the real world. It was marked by a blue circle on the floor of the virtual environment (Fig. 2E). Therefore, when the participants moved their body to another place, the Zero Point (and hence the blue circle) moved with it correspondingly. The idea was that the Zero Point represented the location of the participant's visual 1PP in the virtual environment. Second, Avatar Position referred to the position of the simulated avatar in the virtual environment, marked by a red circle (Fig. 2D, E). In the 1PP conditions (Experiment 1), the Zero Point overlapped with the Avatar Position (so only the red circle was shown in the scene) (Fig. 1B). When the participants looked down at their body, instead of seeing their real body, they would see a life-sized avatar in an orange jacket standing in a red circle, vivid and with shadows in a virtual indoor stadium. In the 3PP conditions (Experiments 2 ~ 5), Avatar Position was programmed to be located at the right-front side (45°) of Zero Point about 45 cm away. Therefore, when the participants looked down at their body, they would see nothing there but an empty blue circle (Fig. 2E). Rather, they would need to look to the right-front about 45° in order to see the avatar (Figs. 2B and D, 5B and D).

3.4 Passive visual-tactile stimulation

To provide tactile stimulations that integrate real and virtual experiences, a VR tracker was attached to a real-world object (baseball bat). An experimenter used the baseball bat to tap on different places of the participant's body for 60 s in the following order: right shoulder, right leg, left leg, left shoulder and then the right shoulder again. The frequency of tapping was approximately once every second. During the tapping session, the participant watched the avatar being tapped by a virtual bat (Figs. 2B and D, 5B). Thus, in the synchronous condition, the participants would not only feel tactile sensations on various places of their

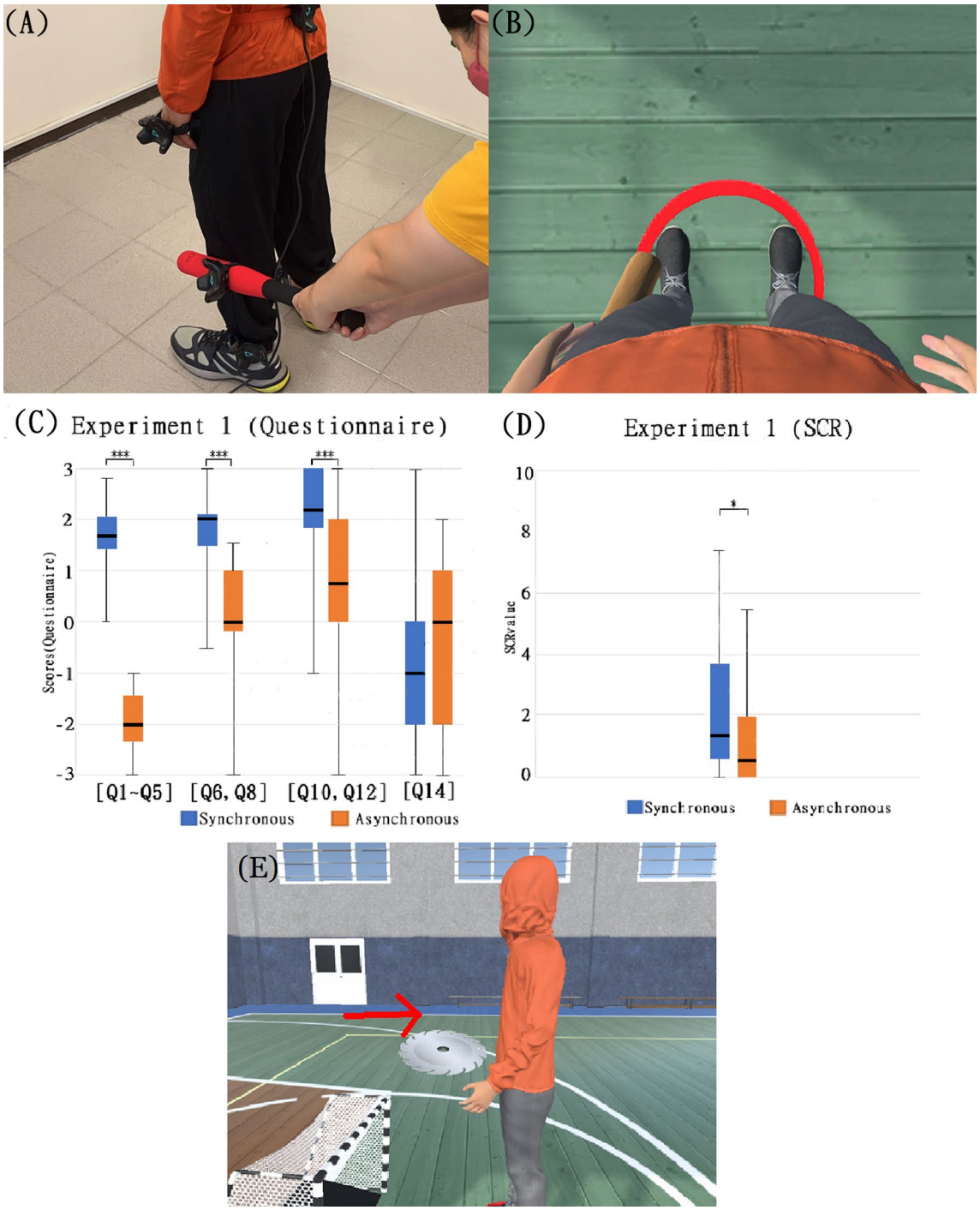


Fig. 1 The setup and results of Experiment 1. **A** The experimental setup viewed from an observer's perspective. **B** The VR scene seen by the participant. The Zero Point overlapped with the Avatar Position, so only the red circle was shown on the scene. When the participants looked down toward their body, instead of seeing their real body, they would see a life-sized avatar in an orange jacket standing in a red circle, vivid and with shadows in a virtual indoor stadium. **C** The box chart of each category of questions of Experiment 1. **D** The box chart of the SCR values of Experiment 1. **E** Presentation of threat by a virtual circular saw blade flying noisily toward the avatar for the SCR measurement. Bold lines indicate the medians; upper and lower limits of the box plot indicate the 75th and 25th percentile. The error bars represent the whole range of the ratings of the statement. Significance levels: $*p < 0.05$; $**p < 0.01$; $***p < 0.001$

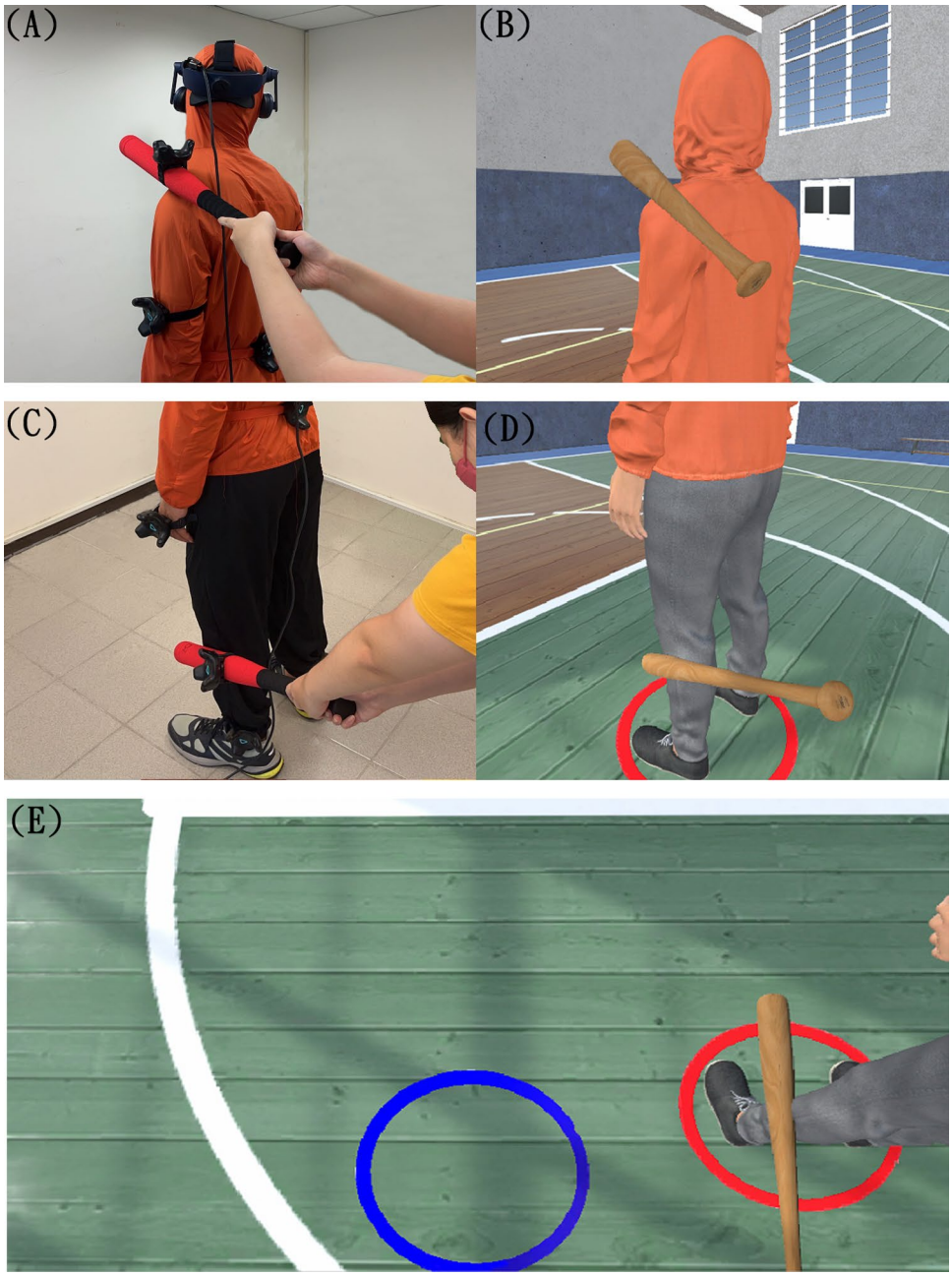


Fig. 2 The setup of Experiments 2 and 3. **A** The experimental setup viewed from an observer's perspective when the participant was touched on the shoulder. **B** The VR scene seen by the participant while being touched on the shoulder. The Avatar Position was programmed to be located at the right-front side (45°) of Zero Point about 45 cm away. **C** The experimental setup viewed from an observer's perspective when the participant was touched on the leg. **D** The VR scene seen by the participant while being touched on the leg. **E** When the participants looked down at their body, they would see nothing there but an empty blue circle

body, but also simultaneously see the avatar being touched on the corresponding body parts by a virtual baseball bat. In the asynchronous condition, the experimenter tapped the participant's shoulders and legs in random order such that the locations and frequency of the tactile sensations felt by the participant did not match the virtual tapping that the participant saw on the avatar.

3.5 Active visual-motor-tactile stimulation

We created a novel way of providing visual-motor-tactile stimulations in this study. A motion tracker (VIVE Tracker 2.0 with three-axis stabilizer) was placed inside a plastic soccer ball such that the tracker could rotate with the ball and remain steady in the center of the ball (Fig. 5C). This allowed the kicking movement of the avatar in the virtual environment (Fig. 5D) to be fully synchronized with the participant's kicking movement in the real world. In Experiments 4 and 5, the participant was instructed to kick the soccer ball into a goal for 4 min. In the synchronous condition, when the participants kicked the plastic soccer ball, they would feel the corresponding tactile sensations on their foot and see the avatar kicking the virtual soccer ball at the same time in the same posture. In the asynchronous condition,

all motion trackers were turned off such that the participant had no control of the avatar. What they watched was a pre-recorded film of the avatar kicking the virtual soccer ball into the goal. Thus, the participant performed the kicking movement but did not get corresponding visual and tactile feedback, and the kicking would often miss the plastic soccer ball.

3.6 Self-location measurements

We used two different ways to measure self-location. *Mental Imagery Task* (MIT): This method was modified from Nakul et al. (2020). In the VR environment, the participants stood still, held a controller, looked to the right-front about 45° and saw a volleyball (about the height of their eyes) rolling straight towards them. The ball rolled past the Avatar Position towards the Zero Point (Fig. 3A). The participants were instructed to click the controller as soon as they felt the rolling ball to be *closest to them*. It was programmed to take exactly 2.58 s for the ball to reach the Avatar Point and exactly 3 s to reach the Zero Point. The ball would stop once the participant clicked the controller. There was a training block of six trials for the participant to become familiarized with the rolling route and the speed of the ball. The participant did two blocks of MIT in Experiments 2 and 4, one block before the tapping session (pre-test) and the other after the questionnaire (post-test). Each block consisted of three rounds of MIT, and the participant's reaction times were recorded and averaged. Following Nakul et al. (2020), we hypothesized that if the participant's sense of self-location shifted toward the Avatar Position due to experimental manipulations, the average difference in reaction time between the pre-test and post-test would be larger in the synchronous conditions than in the asynchronous conditions.

Color Ball Task (CBT): We designed the CBT as a different way of measuring the sense of self-location, and conducted it in Experiments 2 and 4. The participants saw five 3D color-balls spaced evenly apart in front of them (Fig. 3B). From left to right, the colors were green, blue, purple, red and yellow. The green ball was located at the front-left of the Zero Point. The blue ball was directly in front of the Zero Point, i.e. the 1PP position. The purple ball was in between the blue and the red ones. The red ball was located directly in front of the Avatar Position, i.e. the 3PP position. Finally, the yellow ball was at the front-right of the Avatar Position. When the five color-balls appeared together to the participants, they were instructed to answer the question: "Which ball do you feel to be closest to you?" Multiple choices were allowed. The participant did CBT twice in both Experiments 2 and 4, one after the pre-test of MIT (pre-test) and the other after the post-test of MIT (post-test). We hypothesized that participants' answers would be based on their sense of self-location before and after the experimental manipulations.

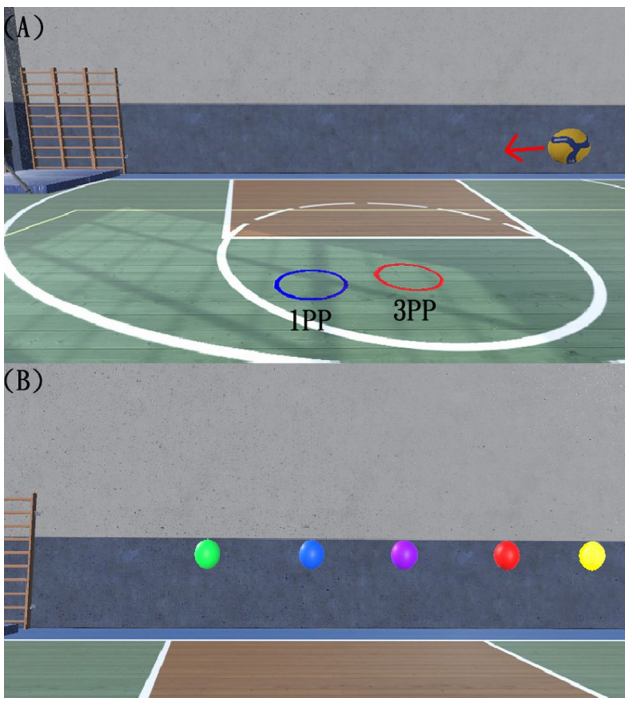


Fig. 3 **A** The setup of the Mental Imagery Task (MIT) in Experiments 2 and 4. **B** The setup of the Color Ball Task (CBT) in Experiments 2 and 4

3.7 Skin conductance responses (SCR)

To record participants' skin conductance responses (SCR) in Experiments1, 3 and 5, we used a Data Acquisition Unit Biopac MP35 (Goleta, USA). We attached two single-use foam electrodes (Covidien, Inc., Mansfield, USA) to the inner side of the participant's left palm. One was placed 2 cm below the thumb and the other 4 cm below the little finger. SCR was measured by presenting a threat—a virtual circular saw blade flying noisily toward the avatar (Fig. 1E). The blade disappeared after it touched the abdomen of the avatar for 5 s. To analyze SCR, the sampling rate was set at 200 samples per second, and the Hardware Filter was set to 20 kHz Lowpass. Data were analyzed with the Biopac software AcqKnowledge v. 3.7.7. We followed the standard procedure and identified the amplitude of SCR as the difference between the maximal and minimal values of the responses within 5 s of the threat.

3.8 Questionnaire

The questionnaire was conducted in Experiments 1, 2 and 4. We used a Likert scale from "strongly disagree" (−3) to "strongly agree" (+3). After each of the experiments, the participants were informed that they would orally answer a

questionnaire presented on their HMD. They were advised to give their answers spontaneously based on their subjective feeling rather than on reasoning. The questions were randomly distributed and were divided into the following categories: body ownership **[Q1 ~ Q5]**, body-location at the Avatar Position **[Q6, Q8]**, body-location at the Zero Point **[Q7, Q9]**, 1PP-location at the Avatar Position **[Q10, Q12]**, 1PP-location at the Zero Point **[Q11, Q13]**, double body-location **[Q14]**, and control question Q15. The questionnaires were in Chinese when presented to the participants. Table 2 presents the English translations.

The 15 statements in each questionnaire were categorized as follows. (1) **[Q1 ~ Q5]**: Q1 was a paradigmatic body ownership question. It measured whether the participants felt the virtual body that they were watching was their own. Q2 was another question of body ownership. Q3 (touch-referral), Q4 (agency) and Q5 (agency) were designed to support the body ownership questions, since touch-referral and agency are often regarded as being correlated with the induction of body ownership experiences (Botvinick and Cohen 1998; Tsakiris 2010; Tsakiris et al. 2006; Jenkinson and Preston 2015; Dummer et al. 2009; Riemer et al. 2013; Chen et al. 2018). Four categories were designed to measure where the subjects experienced their body-location and 1PP-location: (2) **[Q6, Q8]**: Q6 and Q8 were two different ways to measure participants' sense of body-location felt in the Avatar Position. (3) **[Q7, Q9]**: Q7 and Q9 were two different ways to measure the sense of body-location felt at the Zero Point. (4) **[Q10, Q12]**: Q10 and Q12 were two different ways to ask about participants' sense of 1PP-location felt in the Avatar Position. (5) **[Q11, Q13]**: Q11 and Q13 were two different ways to measure the sense of 1PP-location felt at the Zero Point. (6) **[Q14]**: Q14 was the key question of double body-location. It measured whether the participants might feel as if their body was located at two different places at the same time. This was inspired by our previous findings that it is possible for healthy subjects to experience having two bodies (Huang et al. 2017) or having one more pair of hands (Chen et al. 2018). Finally, Q15 was the control question. If any participants answered positively to Q15 in any of the trials, that would be regarded as failing the control, and their data would be removed from our data records. The questionnaires were in Chinese when presented to the participants. Table 2 presents the English translations. The validity of all categories is reported in the Results section (§4.7).

3.9 Procedures

3.9.1 Experiment 1 (Passive 1PP conditions, Sync. vs. Async)

The VR program simulated the participant's body from the 1PP. That is, the avatar appeared at the Zero Point, such that the Avatar Position overlapped with the Zero Point. Standing still, the participant wore an HMD and saw the avatar from the 1PP. An experimenter used a baseball bat to tap on the participant's body for 60 s either synchronously or asynchronously with respect to the virtual tapping on the avatar that the participant saw via the HMD. After the tapping session, SCR was measured, followed by the questionnaire.

3.9.2 Experiment 2 (Passive 3PP conditions, Sync. vs. Async)

The VR program simulated the participant's body with an avatar from the 3PP. That is, the avatar appeared at the right-front side (45°) of the Zero Point about 45 cm away. Standing still, the participants wore an HMD and turned their head to the right-front to see the life-sized avatar. Before the experiment started, the participants were trained to do MIT to be familiarized with the instructions and procedures. Then, in the first phase of the experiment, the pre-tests of MIT and CBT were conducted. In the second phase, an experimenter used a baseball bat to tap on the participant's body for 60 s either synchronously or asynchronously with respect to the virtual tapping on the avatar that the participant saw via the HMD. In the third phase, the questionnaire was conducted, followed by the post-tests of MIT and CBT.

3.9.3 Experiment 3 (Passive 3PP conditions, Sync. vs. Async)

Similar to Experiment 2, the participant's body was simulated by an avatar appearing at the right-front side (45°) of the Zero Point about 45 cm away. Standing still, the participants wore an HMD and turned their head to the right-front to see the life-sized avatar. An experimenter used a baseball bat to tap on the participant's body for 60 s either synchronously or asynchronously with respect to the virtual tapping on the avatar that the participant saw via the HMD. After the tapping session, a threat was presented to the participant (a virtual flying circular saw blade) to measure SCR.

3.9.4 Experiment 4 (Active 3PP conditions, Sync. vs. Async)

The participant's body was again simulated from the 3PP. The participant wore an HMD and saw a life-sized avatar standing on the right-front side about 45 cm away. Before the experiment started, there were training blocks for the participants to be familiarized with MIT. In the first phase, the pre-tests of MIT and CBT were conducted. In the second phase, the participant stood still, and an experimenter used a baseball bat to tap on the participant's body for 60 s either synchronously or asynchronously with respect to the virtual tapping on the avatar that the participant saw via the HMD. In the third phase, a virtual soccer ball and a small soccer

goal appeared on the scene near the avatar, and a plastic soccer ball was put on the lab's floor near the participant. The participant was instructed to kick the soccer ball into the goal. In the synchronous condition, the kicking movement of the avatar that the participant saw nicely matched the participant's own kicking movement. That is, when the participants kicked the plastic soccer ball, they would simultaneously feel the corresponding tactile sensations on their foot. In the asynchronous condition, the participant had no control of the avatar. This phase lasted for 4 min. In the final phase, the questionnaire was conducted, followed by the post-tests of MIT and CBT.

3.9.5 Experiment 5 (Active 3PP conditions, Sync. vs. Async)

Like Experiment 4, the participant wore an HMD and saw a life-sized avatar standing on the right-front side about 45 cm away. The first phase was the same tapping session. The participant stood still, and an experimenter used a baseball bat to tap on the participant's body for 60 s either synchronously or asynchronously with respect to the virtual tapping on the avatar that the participant saw via the HMD. In the second phase, a virtual soccer ball and a small soccer goal appeared on the scene near the avatar, and a plastic soccer ball was put on the lab's floor near the participant. The participant was instructed to kick the soccer ball into the goal. The synchronous and the asynchronous conditions were carried out in the same way as Experiment 4. This phase lasted for 4 min. In the final phase, a threat was presented to the participant (a virtual flying circular saw blade) to measure SCR.

3.9.6 Data analysis

The Shapiro–Wilk tests showed that the questionnaire scores and the SCR data were not normally distributed. To compare the synchronous and asynchronous conditions within each experiment, we used nonparametric Wilcoxon signed-rank tests (two-tailed) to conduct construct analyses. In the cross-experiment analyses, we chose nonparametric longitudinal data fixed models (nparLD) for factorial analyses, followed by Mann–Whitney tests or Wilcoxon signed rank tests for the post-hoc multiple comparisons. Finally, to test the validity of our questionnaire, we also conducted relevant confirmatory factor analyses.

4 Results

Below we present the main experimental results. For more details, see the Supplementary Information.

4.1 Experiment 1: passive 1PP condition (Questionnaire + SCR)

In Experiment 1, the VR program simulated the participant's body from the 1PP, i.e., the avatar appeared at the Zero Point. Since the Avatar Position and the Zero Point overlapped, Q7, Q9, Q11, Q13 were unnecessary. The participant received tactile stimulations and watched an avatar via an HMD from the 1PP being tapped either synchronously or asynchronously (Fig. 1A, B). The box charts of each category of questions and SCR values are shown in Fig. 1C and D. By the two-tailed Wilcoxon signed-rank test on **[Q1 ~ Q5]** ($V = 210$, $p < 0.001$, $Rc = 1.000$) and on SCR ($V = 172$, $p = 0.011$, $Rc = 0.816$), the results were significant between the synchronous and asynchronous manipulations. The same tests on **[Q6, Q8]** ($V = 187.5$, $p < 0.001$, $Rc = 0.974$) and on **[Q10, Q12]** ($V = 148$, $p < 0.001$, $Rc = 0.935$) were also significant. As expected, these results suggest that in the synchronous condition the participants felt that the virtual body was their own. They also felt that both their body-location and 1PP-location were co-located at the Avatar Position (overlapping with the Zero Point).

4.2 Experiment 2: passive 3PP condition (Questionnaire + MIT + CBT)

In Experiment 2, the VR program simulated the participant's body from the 3PP: the avatar appeared at the right-front side (45°) of the Zero Point about 45 cm away. The participant received tactile stimulations and watched via the HMD the avatar located on the right-front side being tapped either synchronously or asynchronously (Fig. 2A, B, C, D, E). The box charts of each category of questions and MIT values are shown in Fig. 4A and B. By the Wilcoxon signed-rank test, **[Q1 ~ Q5]** ($V = 210$, $p < 0.001$, $Rc = 1.000$) was significant between the synchronous and asynchronous conditions, suggesting that the sense of ownership over the avatar was induced in the synchronous condition.

Regarding body-location, the comparison of **[Q6, Q8]** was significant ($V = 171$, $p < 0.001$, $Rc = 1.000$), which suggests that in the synchronous condition the participants felt as if their body-location was in the Avatar Position. Although the comparison of **[Q7, Q9]** was not significant ($V = 23.5$, $p = 0.129$, $Rc = -0.484$), its medians were very high in both the synchronous (med. = 2.25) and asynchronous (med. = 2.50) conditions, indicating that the sense of body-location was strong at the Zero Point regardless of the type of manipulation. Remarkably, the results of double body-location **[Q14]** were significantly higher in the synchronous condition than in the asynchronous condition ($V = 111$, $p = 0.027$, $Rc = 0.519$). Together, these results suggest that the participants felt as if their body was located both at the Zero Point and at the Avatar Position simultaneously.

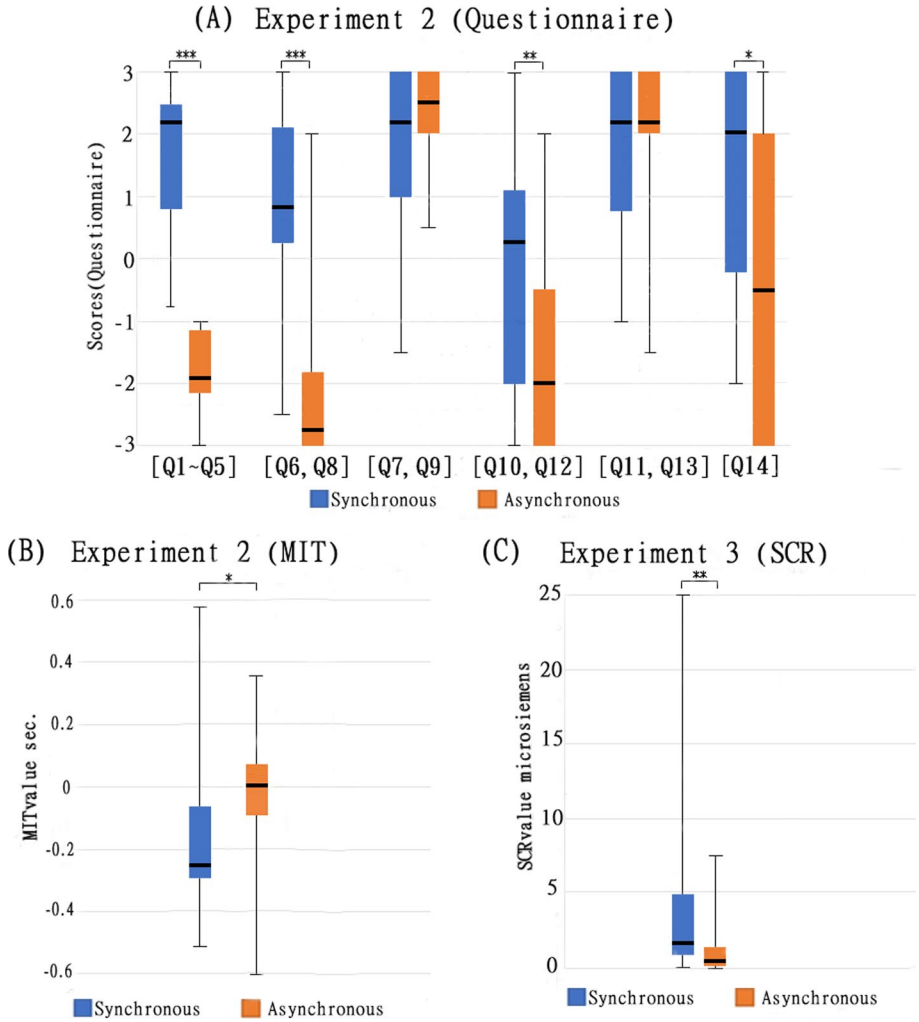


Fig. 4 The results of Experiments 2 and 3. **A** The box chart of each category of questions of Experiment 2. **B** The box chart of MIT results of Experiment 2. **C** The box chart of SCR values of Experiment 3. Bold lines indicate the medians; upper and lower limits of the box plot indicate the 75th and 25th percentile. The error bars represent the whole range of the ratings of the statement. Significance levels: $*p<0.05$; $**p<0.01$; $***p<0.001$

Regarding 1PP-location, the comparison of **[Q10, Q12]** was significant ($V=122.5$, $p=0.005$, $Rc=0.801$), suggesting that it was possible for the sense of 1PP-location to be felt at the Avatar Position. Although the comparison of **[Q11, Q13]** was not significant, the medians in the synchronous (med. = 2.25) and the asynchronous (med. = 2.25) conditions were both very high, indicating that a clear sense of 1PP-location was felt at the Zero Point. Finally, in the MIT task, the participants' reaction-time difference was significantly greater in the synchronous condition than in the asynchronous condition ($V=51$, $p=0.046$, $Rc=0.244$), indicating that due to the manipulations, their sense of self-location drifted towards the Avatar Position to some extent. Interestingly, regarding CBT, all the participants reported that it was the blue ball, which marked the Zero Point, that was closest to them.

4.3 Experiment 3: passive 3PP condition (SCR)

The set-up and the visual-tactile manipulations in Experiment 3 were the same as those in Experiment 2, except that we measured only SCR in Experiment 3. The SCR results ($V=183$, $p=0.002$, $Rc=0.865$) showed that there was a significant difference between the synchronous and the asynchronous conditions (Fig. 4C). This suggests that a strong sense of ownership over the avatar was induced in the synchronous condition.

4.4 Experiment 4: active 3PP condition (Questionnaire + MIT + CBT)

In Experiment 4, the participant's body was again simulated from the 3PP: the avatar appeared at the right-front side (45°) of the Zero Point about 45 cm away. The participants

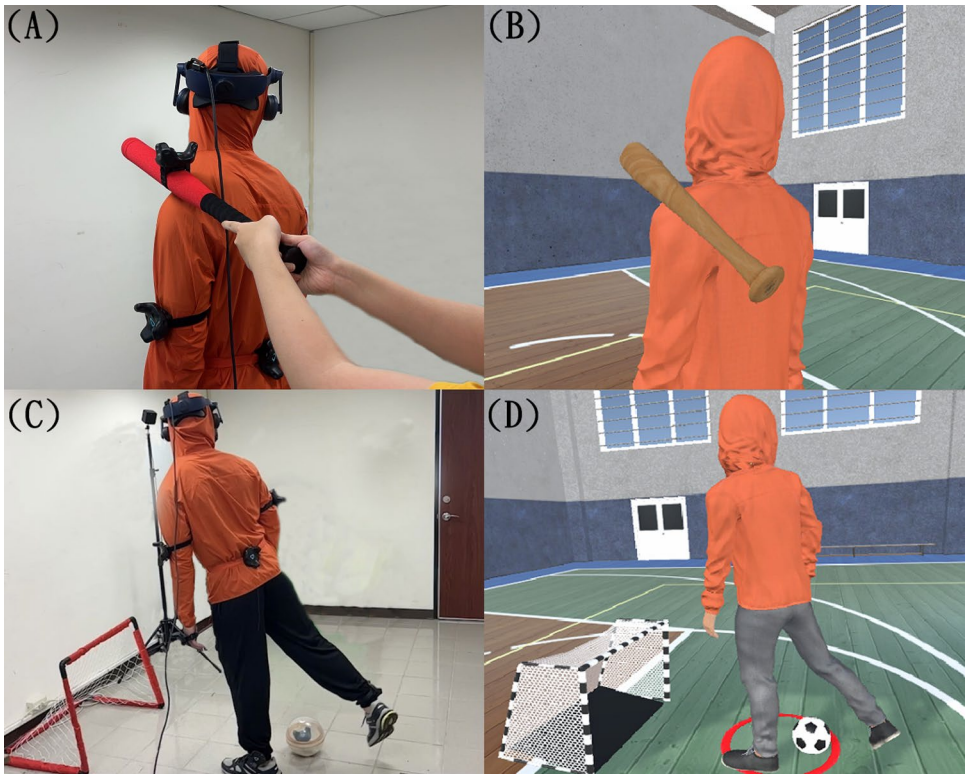


Fig. 5 The setup of Experiments 4 and 5. **A** The experimental setup viewed from an observer's perspective when the participant was touched on the shoulder. **B** The VR scene seen by the participant while being touched on the shoulder. The Avatar Position was programmed to be located at the right-front side (45°) of Zero Point about 45 cm away**. C** The experimental setup viewed from an observer's perspective when the participant was kicking the soccer ball. **D** The VR scene seen by the participant while kicking the soccer ball

saw a virtual body from the 3PP on the right-front side, received synchronous or asynchronous tactile stimulations, and actively interacted with a virtual soccer ball either synchronously or asynchronously (Fig. 5A, B, C, D). The box charts of each category of questions and MIT values are shown in Fig. 6A and B. According to the Wilcoxon signed-rank test, **[Q1 ~ Q5]** ($V = 210$, $p < 0.001$, $Rc = 1.000$) was significant between the synchronous and asynchronous manipulations, suggesting that a strong sense of ownership over the avatar was induced in the synchronous condition.

Regarding body-location, the comparison of **[Q6, Q8]** ($V = 210$, $p < 0.001$, $Rc = 1.000$) was significant, suggesting that in the synchronous condition it was possible for the sense of body-location to be felt at the Avatar Position. Although **[Q7, Q9]** was significant ($V = 9$, $p = 0.011$, $Rc = -0.802$), the synchronous results were lower than the asynchronous results. On the one hand, we think this indicates that the participants' sense of body-location at the Zero Point was influenced by the synchronous tactile/agentive manipulations to a certain extent, such that the sense of body-location could be felt at the Avatar Position. Still, on the other hand, the category medians of **[Q7, Q9]** were high in both conditions (Sync. med. = 1.50; Async. med. = 2.50), suggesting that a strong sense of body-location was felt at the Zero Point regardless of the types of manipulations. More importantly, we found that the results of double body-location **[Q14]** were significantly higher in the synchronous condition than in the asynchronous condition ($V = 128$, $p = 0.015$, $Rc = 0.598$). As in Experiment 2, this suggests that in the synchronous condition the participants felt as if their body was simultaneously located at both the Zero Point and the Avatar Position.

Regarding 1PP-location, the comparison of **[Q10, Q12]** ($V = 168.5$, $p < 0.001$, $Rc = 0.971$) was significant, suggesting that it was possible for the sense of 1PP-location to be felt at the Avatar Position. **[Q11, Q13]** ($V = 37$, $p = 0.345$, $Rc = -0.295$) was not significant, but the category medians were high in both conditions (Sync. med. = 1.75; Async. med. = 2.50), suggesting that the participants felt as if their 1PP-location was at the Zero Point. The participants' MIT reaction-time difference in the synchronous condition was significantly larger than in the asynchronous condition ($V = 2.5$, $p < 0.001$, $Rc = 0.014$), indicating that due to manipulations, their sense of self-location drifted toward the Avatar Position to some extent. In the CBT task, all the participants reported that it was the blue ball, which marked the Zero Point, that was closest to them.

4.5 Experiment 5: active 3PP condition (SCR)

The set-up and the manipulations in Experiment 5 were the same as Experiment 4, except that we measured only SCR in Experiment 5. The SCR results ($V = 210$, $p < 0.001$, $Rc = 0.992$) showed that there was a significant difference between the synchronous and asynchronous conditions

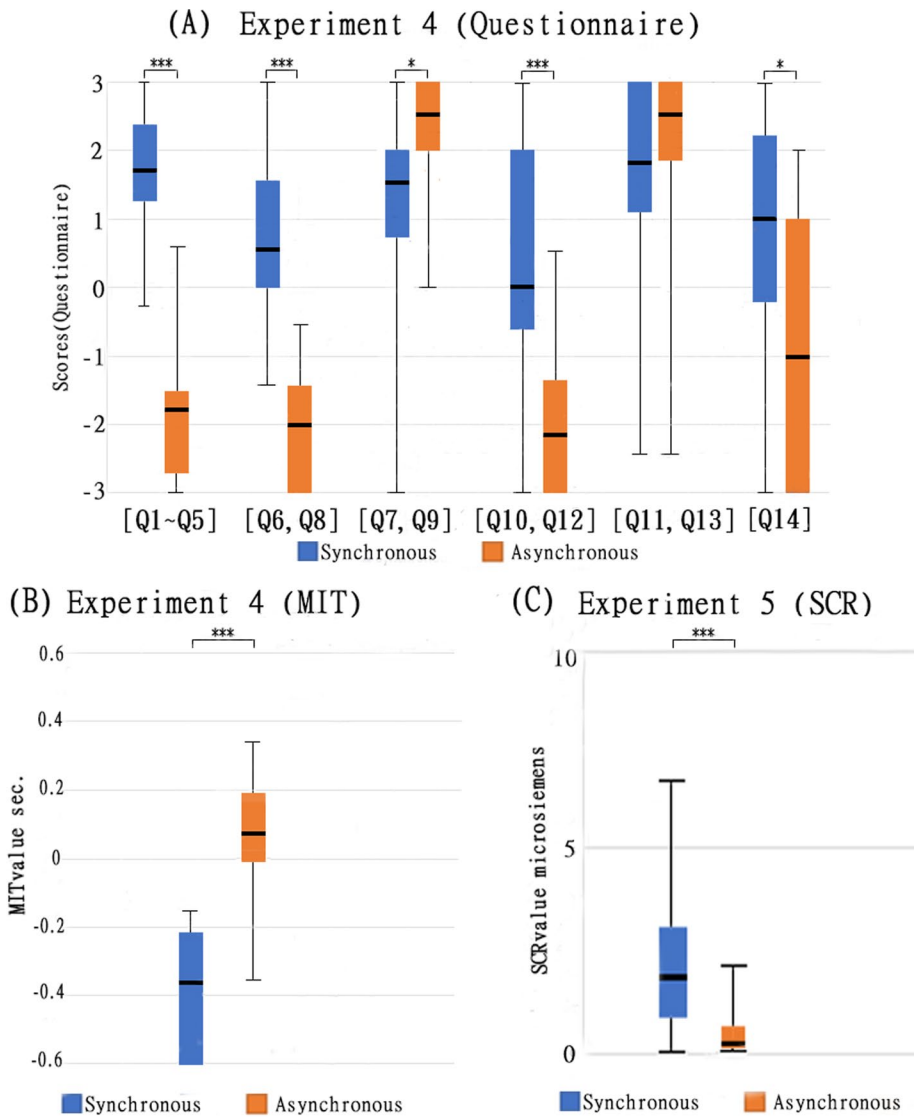


Fig. 6 The results of Experiments 4 and 5. **A** The box chart of each category of questions of Experiment 4. **B** The box chart of MIT results of Experiment 4. **C** The box chart of SCR values of Experiment 5. Bold lines indicate the medians; upper and lower limits of the box plot indicate the 75th and 25th percentile. The error bars represent the whole range of the ratings of the statement. Significance levels: $*p<0.05$; $**p<0.01$; $***p<0.001$

(Fig. 6C). This suggests that a strong sense of ownership over the avatar was experienced in the synchronous condition.

4.6 Cross-experiment analysis

4.6.1 Perspective (1PP vs. 3PP)

We conducted a 2×2 factorial analysis using nonparametric longitudinal data fixed models (nparLD) ANOVA-type statistics to analyze whether the difference in Perspective (1PP or 3PP) influenced the participants' experiences of each construct in the questionnaire. The factors were 2 [Perspective: Experiment 1 (1PP) vs. Experiment 2 (3PP)]×2 [Synchronicity: synchronous conditions vs. asynchronous conditions] factorial analysis. For **[Q1 ~ Q5]**, we found a main effect in Synchronicity ($F=184.78$, $p<0.001$, partial $\eta^2=0.884$) but not in Perspective ($F=0.716$, $p=0.403$, partial $\eta^2=0.019$). This suggests that, given synchronous visuotactile stimulations, the participants experienced the avatar as their own body both from the 1PP and from the 3PP. Regarding **[Q6, Q8]**, there was a main effect both in Synchronicity ($F=69.91$, $p<0.001$, partial $\eta^2=0.637$) and in Perspective ($F=14.58$, $p<0.001$, partial $\eta^2=0.309$). This suggests that the synchronous stimulations helped induce the experience of body-location at the Avatar Position. Although there was a main effect in Perspective, recall that the Avatar Position was co-located with the Zero point in Experiment 1 but not in Experiment 2. Hence, the main effect in Perspective was consistent with our claim in §4.2 that in Experiment 2 the participants felt as if their body-location was at the Avatar Position. Regarding **[Q10, Q12]**, a main effect was again found in Synchronicity ($F=29.00$, $p<0.001$, partial $\eta^2=0.400$) and in Perspective ($F=28.73$, $p<0.001$, partial $\eta^2=0.441$), suggesting that the experience of 1PP-location at the Avatar Position was influenced by both

factors. For **[Q14]**, we found an interaction effect between the two factors ($F = 5.83$, $p = 0.016$, partial $\eta^2 = 0.136$). For multiple comparison in the interaction effect, we conducted additional Mann–Whitney tests and Wilcoxon signed-rank tests and found that the comparison of Perspective was significant when the synchronous conditions were fixed (W = 99, $p = 0.006$), and the comparison of Synchronicity was significant only in Experiment 2 (V = 25, $p = 0.027$). These results indicate that, in Experiment 2 (the synchronous condition) but not in Experiment 1, the participants felt as if their body was located at two different places at the same time.

4.6.2 Activity (active vs. passive)

We conducted several 2 × 2 factorial analyses using nparLD (ATS) to test the effects of the ball-kicking movement on each construct in the questionnaire. The factors were 2 [Activity: Experiment 2 (Passive conditions) vs. Experiment 4 (Active conditions)] × 2 [Synchronicity: Synchronous conditions vs. Asynchronous conditions]. For **[Q1 ~ Q5]**, we found a main effect in Synchronicity ($F = 235.02$, $p < 0.001$, partial $\eta^2 = 0.878$). Regarding **[Q6, Q8]**, there was a main effect in Synchronicity ($F = 114.10$, $p < 0.001$, partial $\eta^2 = 0.735$). For **[Q7, Q9]**, a main effect was observed in Synchronicity ($F = 11.31$, $p = 0.001$, partial $\eta^2 = 0.202$). Regarding **[Q10, Q12]**, a main effect was again found in Synchronicity ($F = 43.45$, $p < 0.001$, partial $\eta^2 = 0.520$). For **[Q11, Q13]**, there was no effect. For **[Q14]**, we once again found a main effect in Synchronicity ($F = 14.80$, $p < 0.001$, partial $\eta^2 = 0.287$). These results suggest that the synchronous ball-kicking movement had robust influences on various aspects of the participants' bodily experiences: the participants felt as if the virtual body was their own body. They also felt as if their body was simultaneously located both at the Avatar Position and at the Zero Point, and as if their 1PP-location was at the Avatar Position.

To test whether the active ball-kicking movement affected the participants' sense of self-location, we tested the effects on the MIT results by a 2 × 2 factorial analysis using nonparametric longitudinal data fixed models (nparLD) ANOVA-type statistics. The factors were 2 [Activity: Experiment 2 (Passive conditions) vs. Experiment 4 (Active conditions)] × 2 [Synchronicity: Synchronous conditions vs. Asynchronous conditions] factorial analysis. We found not only a main effect in Synchronicity ($F = 51.59$, $p < 0.001$, partial $\eta^2 = 0.520$) but also an interaction effect between Synchronicity and Activity ($F = 11.25$, $p = 0.001$, partial $\eta^2 = 0.244$). For multiple comparisons of the interaction effect, we conducted additional Mann–Whitney tests and Wilcoxon signed-rank tests. We found that the comparison of passive and active conditions was significant when the synchronous conditions were fixed (W = 305.5, $p = 0.004$), and it was insignificant when we fixed the asynchronous conditions (V = 139, $p = 0.102$). This suggests that the active ball-kicking movement together with synchronous visual-tactile stimulations contributed to a greater drift of the participants' sense of self-location.

4.7 Confirmatory factor analyses (CFA)

The maximum likelihood estimation with robust standard errors in Mplus was used to conduct CFA, using Chi Square/*df* ratio, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR) as our indicators for model fit to examine the hypothesized factor structure. There were five factors in these analyses: **[Q1 ~ Q5]**, **[Q6, Q8]**, **[Q7, Q9]**, **[Q10, Q12]** and **[Q11, Q13]**. Since the construct **[Q14]** consisted of only one item, Q14, it was not included in the measurement model.

Our model fit indices for CFA are summarized in Table 3. The Chi-Square/*df* ratio was lower than the criterion of 3 (Carmines and McIver 1981). CFI and TLI were higher than the criterion of 0.90 (Bentler 1990). RMSEA was 0.08, which fell within the reasonable fit of 0.05 ~ 0.08 (Browne and Cudeck 1993). SRMR was 0.08, which also fit the criterion of 0.08 (Hu and Bentler 1999). In sum, our model fit indices were reasonably good, suggesting that our 5-factor structure fit the results of each item. Table 4 shows the standardized model results of each item.

5 Discussion

5.1 Full body ownership

In this study, we applied VR technology to investigate the distinction between embodied 1PP and embodied 3PP in

Table 3 Model fit index of factors

Model fit indices	Value
Chi-Square	67.73
df	55
Chi-square/*df*	1.23
CFI	0.93
TLI	0.91
RMSEA	0.08
SRMR	0.08

**CFI*: Comparative fit index; *TLI*: Tucker-Lewis index; *RMSEA*: root mean square error of approximation; *SRMR*: standardized root mean square residual

Table 4 Standardized Model results—STDYX Standardization

Two-Tailed	Estimate	S.E	Est./S.E	*P*-value
[Q1 ~ Q5]				
Q1	0.663	0.111	5.970	0.000
Q2	0.619	0.119	5.191	0.000
Q3	0.757	0.097	7.827	0.000
Q4	0.686	0.111	6.182	0.000
Q5	0.580	0.130	4.456	0.000
[Q6, Q8]				
Q6	0.772	0.077	10.050	0.000
Q8	0.805	0.071	11.293	0.000
[Q7, Q9]				
Q7	0.549	0.145	3.795	0.000
Q9	0.639	0.143	4.459	0.000
[Q10, Q12]				
Q10	0.823	0.082	10.033	0.000
Q12	0.675	0.101	6.683	0.000
[Q11, Q13]				
Q11	1.045	0.111	9.449	0.000
Q13	0.623	0.117	5.342	0.000

relation to bodily self-consciousness. Here we discuss our findings and some relevant previous studies. Experiment 1, the Passive 1PP condition, served as the basis of comparison. As expected, when the avatar was viewed from the 1PP, most participants felt as if the avatar was their own body (call this 1PP body-ownership). In Experiment 2, the Passive 3PP condition, a clear sense of full body ownership of the avatar was induced even when it was viewed from the 3PP. In Experiment 4, the Active 3PP condition, we found that the sense of agency involved in kicking the soccer ball helped to generate the sense of full body ownership of the avatar. These results were supported by the SCR data of Experiments 3 and 5. Together, the results of Experiments 2 ~ 5 made a strong case for the view that it is possible for healthy subjects to experience ownership of a virtual body from the 3PP (call this 3PP body-ownership). This was consistent with some previous studies mentioned in §1 and §2 (Lenggenhager et al. 2007, 2009; Aspell et al. 2009, 2013; Palluel et al. 2011, 2012; Heydrich et al. 2013). Since full body ownership can be experienced both from the 1PP and from the 3PP, this suggests that the distinction between embodied 1PP and embodied 3PP is actually not rigid, but rather a matter of degree.

In the study by Maselli and Slater (2013), immersive VR technologies were used to compare different factors related to the illusion of full-body ownership. The participants sat on a chair, rested their legs on a footstool, and saw via the HMD a virtual body with a similar posture. The virtual body was viewed either from the 1PP or from the 3PP, and the tactile stimulations were either synchronous or asynchronous. It was reported that the full-body ownership illusion was induced only in the 1PP condition, consistent with the study by Petkova et al. (2011). The authors concluded that "a first person perspective over a fake humanoid body is essential for eliciting a body ownership illusion."

We have no objection to the experimental design and data of the study by Maselli and Slater (2013), but we would disagree with their conclusion if it implies that it is not possible for healthy subjects to experience illusory full-body ownership in *any* 3PP set-up. Our results of Experiments 2 ~ 5 have shown that such an implication does not hold. In their study, the participants were sitting still throughout the experiments and passively received tactile stimulations. The only visual sensorimotor contingencies were limited to those provided by head tracking movement. In contrast, the VR system of our Experiment 4 allowed the participants to have a much wider range of bodily movement. Our participants were not only able to move their head and limbs with respect to the virtual body, they also actively interacted with a moving object in both the physical and the virtual reality. By intensifying visuo-motor-tactile contingencies in this way, the conclusions by Maselli and Slater (2013) and by Petkova et al. (2011) do not apply to our current study. 3PP body-ownership is empirically possible. Hence, there is no fundamental gap between 1 and 3PP with regard to full body ownership.

In the study by Debarba et al. (2017) the participant watched an avatar, tried to reach virtual objects and walked straight to the edge of a wooden ramp in a virtual environment. The participants saw the avatar either from the 1PP or from the 3PP and received tactile stimulations by feeling the edge of the ramp with their feet. Based on their results, the authors suggested that "illusory ownership of a virtual body can be achieved in both first- and third-person perspectives under congruent visual-motor-tactile condition." The results of our study were consistent with Debarba et al. (2017). More importantly, our study provided a stronger support for 3PP full-body ownership than Debarba et al. This can be explained by a few methodological differences between the two studies. First, while the virtual body in Debarba et al. was overall white and blank, our avatar was much more vivid. Second, the scope of tactile stimulations in Debarba et al. was limited to the bottom of the participant's feet. In our experiments, the participant received tactile stimulations on both arms and both legs. Finally, and most importantly, the visuo-motor-tactile contingencies in our study involved active interactions with a dynamic object (soccer ball kicking) coordinated between the real and the virtual worlds. This was much more sophisticated than the simple walking and reaching movements in Debarba et al. These differences and our experimental results show that the sense of full-body ownership over the avatar can be induced not only from the 1PP but also from the 3PP in multiple ways.

5.2 Body-location, 1PP-location and self-location

As expected, in Experiment 1, the participants' sense of body-location was in line with their 1PP. Their sense of body-location matched their sense of 1PP-location just like in daily life, and they did not feel as if they had two body-locations. In contrast, the results of Experiments 2 and 4 showed that it is possible for healthy subjects to experience their body as being located simultaneously in two different places, that is, the sense of *double body-locations* **[Q14]** was induced in the synchronous conditions. One of the body-locations was felt to be at the Zero Point **[Q7, Q9]**, which matched the position of the participant's 1PP. The other body-location was felt to be at the Avatar Position **[Q6, Q8]**. We think that the sense of body-location at the Zero Point was sustained by the participant's proprioception, and the body-location at the Avatar Position was due to the experimental manipulations, including synchronous visual-tactile (Experiments 2) and visual-motor-tactile (Experiment 4) stimulations that caused the proprioceptive sense to be partially captured to the 3PP position (Tsakiris and Haggard 2005; Butler et al. 2017; Walsh et al. 2011). Since it is possible to experience the location of one's body both from the 1PP and from the 3PP, this further supports the view that the difference between embodied 1PP and embodied 3PP is a matter of degree.

Regarding 1PP-location, the results of Experiments 2 and 4 suggest that the sense of 1PP-location could be felt not only at the Zero Point **[Q11, Q13]** but also at the Avatar Position **[Q10, Q12]**. The sense of 1PP-location at the Avatar Position was weaker than the sense of 1PP-location at the Zero Point but still significantly stronger than the asynchronous conditions. We think that this was due to the effect of visual capture caused by the visual-tactile stimulations in Experiment 2 and the visuo-motor-tactile stimulations in Experiment 4 (Huang et al. 2017). Since in Experiments 2 and 4 it is possible to experience the 1PP-location both at the Zero Point and at the Avatar Position, this provides additional support for the view that the difference between embodied 1PP and embodied 3PP is not rigid.

We measured self-location by conducting the Mental Imagery Task (MIT) and Color Ball Task (CBT) in Experiments 2 and 4. While CBT was a static measurement, MIT was a dynamic one. The results of CBT in both experiments indicated that the participants' sense of self-location was felt to be only at the Zero Point. However, the results of MIT in both experiments showed that, compared with the asynchronous conditions, the participants in the synchronous conditions felt that they drifted toward the Avatar Position to a certain extent. This was consistent with some previous studies mentioned in §1 and §2 (Lenggenhager et al. 2007, 2009; Aspell et al. 2009, 2013; Ionta et al. 2011; Heydrich et al. 2013), as well as the recent study by Nakul et al. (2020), who first suggested the method of MIT in VR research. Notice that the drift of self-location did not really reach as far as the Avatar Position. The point is that feeling one's self in between the Zero Point and the Avatar Position was still an experience of self-location not from the 1PP but from a 3PP. Hence, the results of CBT and MIT together provide yet another way to diminish the distinction between embodied 1PP and embodied 3PP.

It is worth mentioning that these experimental results enable us to shed new light on the nature of self-location. Many researchers understand self-location merely in terms of body-location. For example, in Serino et al. (2013), self-location was depicted as "the experience of being a body with a given location within the environment". Maselli and Slater (2014) also described self-location as "the experience of the body occupying a given portion of space in the environment". In the fMRI study by Guterstam et al. (2015), self-location was defined as "the experience that the body is located somewhere in space". These views simply assume that self-location and body-location are the same phenomenon. However, it is not clear whether this assumption is correct. While the data of body-location in Experiments 2 and 4 suggest that it is possible for healthy subjects to experience double body-locations, the results of CBT and MIT did not indicate a similar possibility of "double experience" with regard to self-location. Also, one of our previous studies posed a challenge to the above assumption (Huang et al. 2017). We showed in that study that body-location and 1PP-location are dissociable and hence are different subjective experiences. Thus, in addition to body-location, the contribution of 1PP-location to the sense of self-location should be taken into consideration. We suggest that self-location is better understood as being jointly underpinned by two interrelated but distinct factors: body-location and 1PP-location.

5.3 Bodily experience and virtual reality

In this sub-section, we compare our study with some previous works in VR research. In Gonzalez-Franco et al. (2020), the authors describe the "self-avatar follower effect" as follows: "whenever the virtual body does not overlay with their physical body, users tend to unconsciously follow their avatar, filling the gap if the system allows for it." Although this follower effect is not the main target of our study, several findings of our experiments seem to be compatible with it. Recall, in the 3PP conditions, when the participants looked down at their body, they would see nothing there (Fig. 2E). The participants needed to look to the right-front about 45° in order to see the avatar (Figs. 2B and D, 5B and D). This setup clearly fits what Gonzalez-Franco et al. (2020) call "spatial misalignment". Our experimental results showed that, under suitable manipulations, the participants could experience 3PP body-ownership, 3PP body-location, and

drift of self-location towards a 3PP position. To some extent, these results seem to fit the observation by Gonzalez-Franco et al. (2020) that "participants will accommodate their own body positioning to match that of the avatar they are embodying. If an offset is introduced participants will have the tendency to reduce it."

However, at this stage, we are not prepared to claim that our findings are examples of the follower effect because the participants of our experiments also experienced 1PP body-location as well as 1PP-location at the Zero-point. Also, since in our Experiments 2 and 4 the sense of double body-locations was induced in the synchronous conditions, it is not clear whether in our experiments "the seen virtual body and the physical body experienced through somato-sensations are interpreted as the *same* body" (Gonzalez-Franco et al. 2020). Therefore, it would probably require further study to ascertain the exact relationship between the follower effect and the bodily experiences investigated in our study.

In the study by Day et al. (2019), participants were assigned to either a normal avatar or an altered avatar with a lengthened arm and were instructed to perform reaching tasks. The results showed that "feedback allowed participants to calibrate to an avatar with lengthened arms, and this calibration carried over to a subsequent posttest phase where the feedback was removed." The authors discussed how their results related to the notion of body schema. According to Day et al. (2019), "A body schema is a stable representation of the body and its potential for action." They further suggested that the calibration effect shown in their experiments indicated that the body schema is malleable and that "The body schema does not seem to distinguish between objects and limbs, but rather it represents the effects of a tool as the lengthening of the arm."

We agree with Day et al. (2019) on the role of feedback and calibration. We also have no problems with their data interpretation in terms of body schema. However, one might be motivated by Day et al. (2019) to interpret our experimental results as the avatar viewed from the 3PP being essentially a tool used by the participant to interact with the virtual soccer ball. If so, we would not concur with this interpretation of our findings. First, we think that there is a difference between using the avatar as a tool and experiencing the avatar as one's own body. As de Vignemont (2018: 45) argues in her book on bodily self-consciousness: "[O]ne can experience referred sensations in tools. Thanks to these sensations one experiences the tools as being part of a larger space on which they can act. […] *Yet one may feel no ownership for them*" (our emphasis). The reason is that the bodily representation that is primarily responsible for body ownership is distinct from body schema, which is primarily responsible for tool use (de Vignemont 2018: 179–181). Second, in the research on bodily self-consciousness, it is widely accepted that SCR provides physiological evidence for illusory bodily experiences (Armel and Ramachandran 2003; Petkova and Ehrsson 2008; Chen et al. 2018). We highly suspect that threatening a tool would not generate SCR results as high as threatening one's body. Finally, and most importantly, many neuroscientific studies have shown that tool use and body ownership have different neural mechanisms (Gallivan et al. 2013; Cabrera-Álvarez and Clayton 2020; Miller and Farnè 2023; Tsakiris 2010; Blanke 2012; Ehrsson 2012; Serino et al. 2013; Blanke et al. 2015). More studies will be required to settle this issue.

6 Conclusions

We end the discussion with three concluding remarks: first, we have argued that, when it comes to bodily self-consciousness, there is indeed no fundamental chasm between embodied 1PP and embodied 3PP in the VR environment. We have provided empirical evidence for this view in terms of body ownership, self-location, body-location and 1PP-location. We are not saying that the empirical support from each of these categories, considered separately, was sufficient for establishing our view. However, we do argue that, when taken together, the multifarious evidence presented in this study strongly suggests that the distinction between embodied 1PP and embodied 3PP is at most a matter of degree. Second, we have shown that the experience of 3PP body-ownership is empirically possible, and that the experience of double body-locations is empirically possible as well. These findings will not threaten the philosophical insights mentioned in the beginning of the Introduction, i.e., the view that each conscious self is uniquely associated with a 1PP, and that all conscious experiences are essentially tied to a particular 1PP. We think that these views still hold given our experimental results. It is just that they do not imply the mainstream view mentioned in the Introduction that is undermined by the current study. Finally, for future research, clearly there is a need to further investigate the following: (1) the nature of double body-locations, (2) the relationship between body-location and 1PP-location, and finally (3) the interaction between the experience of embodied 1PP and the experience of embodied 3PP.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10055-023-00907-8.

Acknowledgements The authors would like to thank Yun-Yu He, Chi-Hong Chen, Yi-Jan Wang, Tai-Yuan Chang, Hsiang-Yin Wu, Shang-Yi Chuang and Ssu-Ching Huang for their assistance in our lab. We would also like to thank Professor Chen-Gia Tsai from the Graduate Institute of Musicology for the SCR equipment. Yen-Tung Lee is funded by 2023 National Science and Technology Council Taiwanese Overseas Pioneers Grants (TOP Grants) for PhD Candidates. Finally, this study was supported by National Science and Technology Council of Taiwan (project: NSTC 110-2410-H-002-142-MY2) and by the Empower

Vocational Education Research Center of National Taiwan University of Science and Technology (NTUST).

Author contribution CL designed all experiments; W-KL provided VR technology; W-HL, conducted the experiments; SC, Y-TL, W-HL and CL analyzed the data; CL, Y-TL and W-KL wrote the manuscript.

Funding Ministry of Science and Technology (NSTC 110–2410-H-002–142-MY2).

Data availability All data generated or analyzed during this study are included in this published article and its supplementary information file.

Declarations

Conflict of interest Informed consent to participate was acquired from all participants. The persons whose body shown in the Figures gave their written informed consent to publish. All experiments were conducted in accordance with the Declaration of Helsinki. This study was performed in accordance with the regulations of, and was approved by, the Research Ethics Committee of National Taiwan University (NTU-REC: 202012HM035). The authors declare that they have no competing interests.

References

Armel KC, Ramachandran VS (2003) Projecting sensations to external objects: evidence from skin conductance response. Proc Biol Sci 270(1523):1499–1506

Aspell JE, Lenggenhager B, Blanke O (2009) Keeping in touch with one's self: multisensory mechanisms of self-consciousness. PLoS ONE 4(8):e6488

Aspell JE, Heydrich L, Marillier G, Lavanchy T, Herbelin B, Blanke O (2013) Turning body and self inside out: visualized heartbeats alter bodily self-consciousness and tactile perception. Psychol Sci 24(12):2445–2453

Baker LR (2000) Persons and bodies: a constitution view. Cambridge University Press, Cambridge

Bentler PM (1990) Comparative fit indexes in structural models. Psychol Bull 107:238–246

Bergström I, Kilteni K, Slater M (2016) First-person perspective virtual body posture influences stress: a virtual reality body ownership study. PLoS ONE 11(2):e0148060

Blanke O (2012) Multisensory brain mechanisms of bodily self-consciousness. Nat Rev Neurosci 13:556–571. https://doi.org/10.1038/nrn3292

Blanke O, Metzinger T (2009) Full-body illusions and minimal phenomenal selfhood. Trends Cogn Sci 13:7–13

Blanke O, Mohr C (2005) Out-of-body experience, heautoscopy, and autoscopic hallucination of neurological origin: implications for neurocognitive mechanisms of corporeal awareness and self-consciousness. Brain Res Rev 50:184–199

Blanke O, Slater M, Serino A (2015) Behavioral, neural, and computational principles of bodily self-consciousness. Neuron 88(1):145–166

Botvinick M, Cohen J (1998) Rubber hands 'feel' touch that eyes see. Nature 391:756

Browne MW, Cudeck R (1993) Alternative ways of assessing model fit. In: Bollen KA, Long JS (eds) Test structural equation models. Sage, Newbury Park, CA, pp 136–162

Butler AA, Héroux ME, Ganderia SC (2017) Body ownership and a new proprioceptive role for muscle spindles. Acta Physiol 220:19–27

Cabrera-Álvarez MJ, Clayton NS (2020) Neural processes underlying tool use in humans, macaques, and corvids. Front Psychol 11:560669

Carmines EG, McIver JP (1981) Analyzing models with unobserved variables: Analysis of covariance structures. In: Bohrnstedt W, Borgatta EF (eds) Social measurement: current issues. Sage, Newbury Park, CA, pp 65–115

Chen WY, Huang HC, Lee YT, Liang C (2018) Body ownership and the four-hand illusion. Sci Rep 8:2153

Christoff K, Cosmelli D, Legrand D, Thompson E (2011) Specifying the self for cognitive neuroscience. Trends Cogn Sci 15:104–112

Cohen J (1969) Statistical power analysis for the behavioral sciences. Routledge Academic, New York, NY

David N, Bewernick BH, Cohen MX, Newen AN, Lux S, Fink GR et al (2006) Neural representations of self versus other: visual-spatial perspective taking and agency in a virtual ball-tossing game. J Cogn Neurosci 18:898–910

Day B, Ebrahimi E, Hartman LS, Pagano CC, Robb AC, Babu SV (2019) Examining the effects of altered avatars on perception-action in virtual reality. J Exp Psychol Appl 25(1):1–24

de Vignemont F (2018) Mind the body: an exploration of bodily self-awareness. Oxford University Press, Oxford, GB

Debarba HG, Bovet S, Salomon R, Blanke O, Herbelin B, Boulic R (2017) Characterizing first and third person viewpoints and their alternation for embodied interaction in virtual reality. PLoS ONE 12:e0190109

Dummer T, Picot-Annand A, Neal T, Moore C (2009) Movement and the rubber hand illusion. Perception 38:271–280

Ebrahimi E, Robb A, Hartman LS, Pagano CC, Babu SV (2018) Effects of anthropomorphic fidelity of self-avatars on reach boundary estimation in immersive virtual environments. In: Proceedings of the 15th ACM symposium on applied perception (SAP '18), Association for Computing Machinery, New York, NY, USA, Article 2, pp 1–8. https://doi.org/10.1145/3225153.3225170

Ehrsson HH (2007) The experimental induction of out-of-body experiences. Science 317(5841):1048

Ehrsson HH (2012) The Concept of body ownership and its relation to multisensory integration. In: Stein BE (ed) The new handbook of multisensory processing. MIT Press, Cambridge

Gallagher S (2000) Philosophical conceptions of the self: implications for cognitive science. Trends in Cogn Sci 4(1):14–21

Gallagher S (2012) First-person perspective and immunity to error through misidentification. In: Miguens S, Preyer G (eds) Consciousness and subjectivity. Philosophical Analysis Ontos Publisher, Frankfurt, pp 187–214

Gallivan JP, McLean DA, Valyear KF, Culham JC (2013) Decoding the neural mechanisms of human tool use. eLife 2:e00425

Gonzalez-Franco M, Cohn B, Ofek E, Burin D, Maselli A (2020) The self-avatar follower effect in virtual reality. In: 2020 IEEE conference on virtual reality and 3D user interfaces (VR). Atlanta, GA, USA, pp 18–25

Guterstam A, Ehrsson HH (2012) Disowning one's seen real body during an out-of-body illusion. Conscious Cogn 21:1037–1042

Guterstam A, Petkova VI, Ehrsson HH (2011) The illusion of owning a third arm. PLoS ONE 6(2):e17208

Guterstam A, Björnsdotter M, Gentile G, Ehrsson HH (2015) Posterior cingulate cortex integrates the senses of self-location and body ownership. Curr Biol 25(11):1416–1425

Heydrich L, Dodds TJ, Aspell JE, Herbelin B, Bülthoff HH, Mohler BJ, Blanke O (2013) Visual capture and the experience of having two bodies–evidence from two different virtual reality techniques. Front Psychol 4:946

Hu L, Bentler PM (1999) Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives. Struct Equ Model 6:1–55

Huang HC, Lee YT, Chen WY, Liang C (2017) The sense of 1PP-location contributes to shaping the perceived self-location together with the sense of body-location. Front Psychol 8:370. https://doi.org/10.3389/fpsyg.2017.00370

Husserl E (1973) Husserliana 14: zur phänomenologie der intersubjektivität: texte aus dem nachlass, zweiter teil: 1921–1928. Martinus Nijhoff, Den Haag

Ionta S, Heydrich L, Lenggenhager B, Mouthon M, Fornari E, Chapuis D et al (2011) Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. Neuron 70:363–374. https://doi.org/10.1016/j.neuron.2011.03.009

Jenkinson PM, Preston C (2015) New reflections on agency and body ownership: the moving rubber hand illusion in the mirror. Conscious Cogn 33:432–442. https://doi.org/10.1016/j.concog.2015.02.020

Kalckert A, Ehrsson HH (2012) Moving a rubber hand that feels like your own: a dissociation of ownership and agency. Front Hum Neurosci 6:40

Kokkinara E, Kilteni K, Blom KJ, Slater M (2016) First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. Sci Rep 6:28879

Legrand D (2007) Pre-reflective self-as-subject from experiential and empirical perspectives. Conscious Cogn 16:583–599

Legrand D, Ruby P (2009) What is self-specific? Theoretical investigation and critical review of neuroimaging results. Psychol Rev 116:252–282

Lenggenhager B, Tadi T, Metzinger T, Blanke O (2007) Video ergo sum: manipulating bodily self-consciousness. Science 317:1096–1099

Lenggenhager B, Mouthon M, Blanke O (2009) Spatial aspects of bodily self-consciousness. Conscious Cogn 18(1):110–117

Levine J (2001) Purple haze: the puzzle of consciousness. Oxford University Press, Oxford

Liang C (2016) Self-as-subject and experiential ownership. In: Metzinger T, Windt JM (eds) Open MIND: philosophy and the mind sciences in the 21st century, vol 2. The MIT Press, London, pp 957–975

Maselli A, Slater M (2013) The building blocks of the full body ownership illusion. Front Hum Neurosci 7:83. https://doi.org/10.3389/fnhum.2013.00083

Maselli A, Slater M (2014) Sliding perspectives: dissociating ownership from self-location during full body illusions in virtual reality. Front Hum Neurosci 8:693. https://doi.org/10.3389/fnhum.2014.00693

Metzinger T (2003) Being no one. MIT Press, Cambridge

Miller LE, Farnè A (2023) Tool use. In: Alsmith AJT, Longo MR (eds) The routledge handbook of bodily awareness. Taylor & Francis, Routledge, p 22

Nagel T (1974) What is it like to be a bat? Philos Rev 83:435–450

Nakul E, Orlando-Dessaints N, Lenggenhager B, Lopez C (2020) Measuring perceived self-location in virtual reality. Sci Rep 10:6802. https://doi.org/10.1038/s41598-020-63643-y

Palluel E, Aspell JE, Blanke O (2011) Leg muscle vibration modulates bodily self-consciousness: integration of proprioceptive, visual, and tactile signals. J Neurophysiol 105(5):2239–2247

Palluel E, Aspell JE, Lavanchy T, Blanke O (2012) Experimental changes in bodily self-consciousness are tuned to the frequency sensitivity of proprioceptive fibres. Neuroreport 23(6):354–359

Petkova VI, Ehrsson HH (2008) If I were you: perceptual illusion of body swapping. PLoS ONE 3:e3832

Petkova VI, Khoshnevis M, Ehrsson HH (2011) The perspective matters! Multisensory integration in ego-centric reference frames determines full-body ownership. Front Psychol 2:35

Riemer M, Kleinbohl D, Holzl R, Trojan J (2013) Action and perception in the rubber hand illusion. Exp Brain Res 229:383–393

Serino A, Alsmith A, Costantini M, Mandrigin A, Tajadura-Jimenez A, Lopez C (2013) Bodily ownership and self-location: components of bodily self-consciousness. Conscious Cogn 22:1239–1252

Slater M, Spanlang B, Sanchez-Vives MV, Blanke O (2010) First person experience of body transfer in virtual reality. PLoS ONE 5:e10564–e10564

Tsakiris M (2010) My body in the brain: a neurocognitive model of body-ownership. Neuropsychologia 48:703–712

Tsakiris M, Haggard P (2005) The rubber hand illusion revisited: visuotactile integration and self-attribution. J Exp Psychol Hum Percept Perform 31:80–91

Tsakiris M, Prabhu G, Haggard P (2006) Having a body versus moving your body: how agency structures body-ownership. Conscious Cogn 15:423–432

Vogeley K, Fink GR (2003) Neural correlates of the first-person-perspective. Trends Cogn Sci 7:38–42

Vogeley K, May M, Ritzl A, Falkai P, Zilles K, Fink GR (2004) Neural correlates of first-person perspective as one constituent of human self-consciousness. J Cogn Neurosci 16:817–827

Walsh LD, Moseley GL, Taylor JL, Gandevia SC (2011) Proprioceptive signals contribute to the sense of body ownership. J Physiol 589:3009–3021

Wittgenstein L (1958) The blue and brown books: preliminary studies for the "philosophical investigations." Harper & Row, Oxford, England

Yee N, Bailenson J (2007) The proteus effect: the effect of transformed self-representation on behavior. Hum Commun Res 33(3):271–290

Zahavi D (2005) Subjectivity and selfhood: investigating the first-person perspective. Bradford Book/MIT Press, Cambridge MA

Zahavi D (2020) Consciousness and selfhood: Getting clearer on forme-ness and mineness. In: Kriegel U (ed) The oxford handbook of the philosophy of consciousness. Oxford University Press, London, pp 635–653

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.