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ORIGINAL ARTICLE

Effects of invisible body and optic flow on experience of users voluntarily walking in a VR environment

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Abstract

Studies have demonstrated that a multi-modal virtual reality (VR) system can enhance the realism of virtual walking. However, a few studies explore the body awareness altered by visual presentation of virtual body and optic flow during locomotion in VR. This study investigated the impact of invisible body and optic flow on experience of users voluntarily walking in a camera-image VR environment. Participants wearing a head-mounted display performed six-step walking at their own timing. Three experimental conditions providing visible body and optic flow as a baseline, invisible body and optic flow, and invisible body and no flow, were conducted on three different days. We found that losing visual body per se decreased the feeling of being-there-now. However, providing continuous optic flow maintained virtual presence equivalent to the baseline in terms of immersion and natural walking, as opposed to providing discontinuous flow. We discussed these results in association with body awareness.

Keywords Body awareness · Optic flow · Locomotion · VR environment · Voluntary walking

1 Introduction

Applications for virtual reality (VR) help users to immerse themselves in a realistic or imaginative virtual world. Users can interact with a variety of scenes, such as walking, boxing with virtual opponents, and dancing with partners in the virtual world [1]. In the past, a hardware setup that included a stereoscopic display, computers, headphones, speakers, and 3D input devices was referred to as virtual reality [2]. More recently, regardless of the hardware they employ, the word has been used widely to describe any software that contains a 3D component. Given this wide range, it is important to define and define what is meant by virtual reality. A binary definition would make it impossible to compare different VR systems, and hence, the definition of VR should not be that simple. Based on this concept, studies consider a VR system in the context of the VR experience it offers. The replacement of one or more physical senses with virtual senses is the most fundamental definition of a VR experience [3, 4]. When it comes to exploring settings that are difficult for humans to reach or that are highly specialized for a specific purpose, virtual reality technology is a wonderful tool.

Users can enjoy realistic, high-fidelity VR with the help of a variety of devices. A display system, such as a head-mounted display (HMD), that presents images in a way that the user perceives them to be 3D (as opposed to seeing a 2D projection of a 3D scene on a common TV or computer screen) in combination with a head tracking system might be the minimum set of requirements for a highly immersive VR experience, given the relative importance the sense of sight has in our interaction with the world [5, 6]. Therefore, simulating natural walk is predicted to greatly improve navigation in the virtual world, because it mimics how people

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often explore the real world [7–9]. Redirected walking techniques and/or applying a gain to the virtual movement distort the virtual environment to represent a greater space than the actual environment within a border that can be recognized by an external tracker [7, 10]. By stimulating vestibular sensors while maintaining immobility, a treadmill methodology offers navigation options. The body is locked in place with respect to the hardware in the treadmill method as foot movement is monitored along the floor or tread on the unpowered treadmill [11, 12]. However, when trying to simulate natural walking in a virtual world, there have been three basic issues. The first is to develop a responsive gadget that gives the feeling of natural walking. The second is to provide consumers the option to move across virtual areas that are far bigger than the actual ones they are in. The final problem is to create an environment where people can adapt relatively quickly [13].

Especially with respect to the first issue above [13], researches have demonstrated that a multi-modal VR system providing auditory and haptic feedback in addition to optic flow can enhance the realism of virtual walking [14–17]. Although they investigated effects of several external cues on user experience, there are few studies involving existence of user's virtual body during locomotion [18], even though there are many studies interested in its visualization from a technical aspect [19]. Neuropsychological studies have suggested that users can feel the virtual body moving synchronously with them as their body [20, 21], so-called the sense of body-ownership, and feel authorship over one's own actions and controlling their execution [22], so-called the sense of agency.

Having these senses of body awareness contributes to improve the reality of VR experience [23, 24]. In line with this, a study has suggested that even absence of virtual body can elicit virtual walking experience if appropriate sensory feedback is provided to induce the body awareness [18]. It is not clear, though, how the different levels of body awareness influence the user experience in VR. Delving into a relationship between body awareness and the experience is important not only to design an effective VR but also to explore the nature of reality felt in VR environments.

This study addressed how the body awareness tuned by visual presentation on VR affects a virtual presence in VR environments. There were three experimental conditions. In the continuous condition, we assumed that optic flow that was continuously matched to one's own locomotion would induce sufficient body awareness in VR environments even if a virtual body was visually lost [18]. By contrast, in the discontinuous condition, discontinuous optic flow would induce insufficient body awareness because of the lack of visual feedback to sustain sense of agency. These two conditions were compared with a baseline condition where visually close-to-reality presentation was provided. The virtual presence was assessed in terms of the feeling of being-there-now, immersion, and natural walking. We hypothesized that, in comparison with the baseline, the virtual presence was equivalent in continuous condition and declined in discontinuous condition.

2 Materials and methods

2.1 Participants

The participants in this experiment were 12 healthy adults (10 males and 2 females, age 22 ± 6 years), and they had no prior knowledge of the experiment. The experiment was conducted for a total of 3 days under different experimental conditions. The experiment days for each participant were about 1 week apart. On the first day of the experiment, the participants received an overall explanation of the experiment and agreed to participate in the experiment. The experiment was conducted with permission from the Ethics Committee of Nagaoka University of Technology.

2.2 Pre-experiment procedure

Before the start of the experiment on each experimental day, participants received an explanation of the experimental procedure in a waiting room (the room shown in gray in Fig. 1). They were then taken outside the room and put on an HMD (Oculus Rift cv1, Oculus VR, LLC, U.S; a resolution of 1080 × 1200 pixels per eye, a horizontal field of

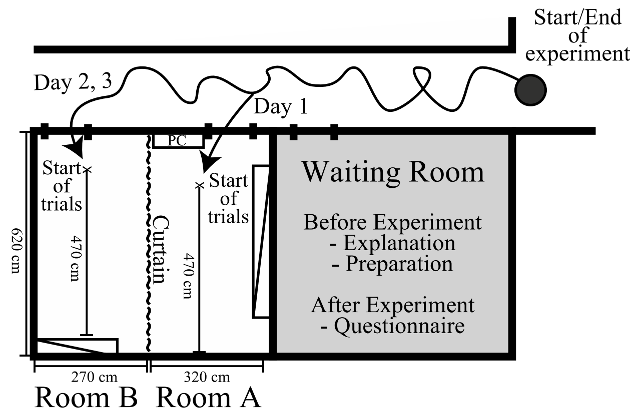

Fig. 1 Schematic diagram of the experimental venue. At first, participants received explanation in the waiting room (gray). They then moved to the experiment start position (black circle) and their eyes were covered with an HMD on which still no images were projected. The experimenter took them along random trajectory (lines with arrows) to the room where experiments were carried out (Room A on the first day or Room B on the second and third days). After participants completed the trials on the day, they were taken out to the end position with their eyes closed. These were because participants could not specify where they performed experiments in 3 days

view of 110°, and a refresh rate of 90 Hz) at the experiment starting position (black circle in Fig. 1). At this time, the HMD was not connected to the control PC and no images were projected. Participants were instructed to close their eyes and guided by the experimenter along a complex trajectory from the starting position to the room where the experiment would be conducted (solid curves with arrows in Fig. 1). This process was to prevent participants from identifying which room all three experiments took place in. In fact, although the experimental room used on the first day was different from the room on the second and the third day (Room A and Room B, respectively, in Fig. 1), the participants did not realize that when asked at the end of the third day. After entering the experimental room, participants were guided to the starting position of experimental walking. Then, the HMD was connected to the PC and images were projected according to the experimental conditions for each day (see the next section), and participants were instructed to open their eyes, look around, and adjust the HMD to make the images clear to see.

2.3 Experimental procedure and conditions

To explore the psychological and kinematic effects of absence of visual bodies and continuous motion images, three experimental conditions with different video presentation methods were used in this study. Participants performed the experimental conditions on different days. Baseline condition was carried out on the first day, and Continuous and Discontinuous conditions were carried out on the second and third days in random order.

Common protocol to three experimental conditions: The actions that participants were instructed to perform were the same in all three conditions. Participants were guided by the experimenter to the trial starting position with their eyes closed and stood with their feet together (start of trial positions represented by crosses in Fig. 1). With their eyes open and looking straight ahead, they took six steps forward at their own timing. After landing on the sixth step, they stood with their other foot together and closed their eyes. Then, they used a stopwatch to report the time it took from landing the first step to landing the sixth step. Keeping their eyes closed, they walked back to the place that they thought the starting position. The experimenter then guided them to the actual starting position. The above protocol was repeated 10 times. At the end of the tenth trial, participants were taken to the experiment end position outside the room (black circle in Fig. 1) with eyes closed along the complicated trajectory as well as the beginning. After removing the HMD, participants were instructed to complete the questionnaire in a waiting room.

Baseline condition (providing visible body and optic flow, close to the real world): In this condition, participants wearing HMD could perceive their body and continuous motion images following their locomotion. Participants were guided to the trial starting position in Room A (Fig. 2a). Real-time

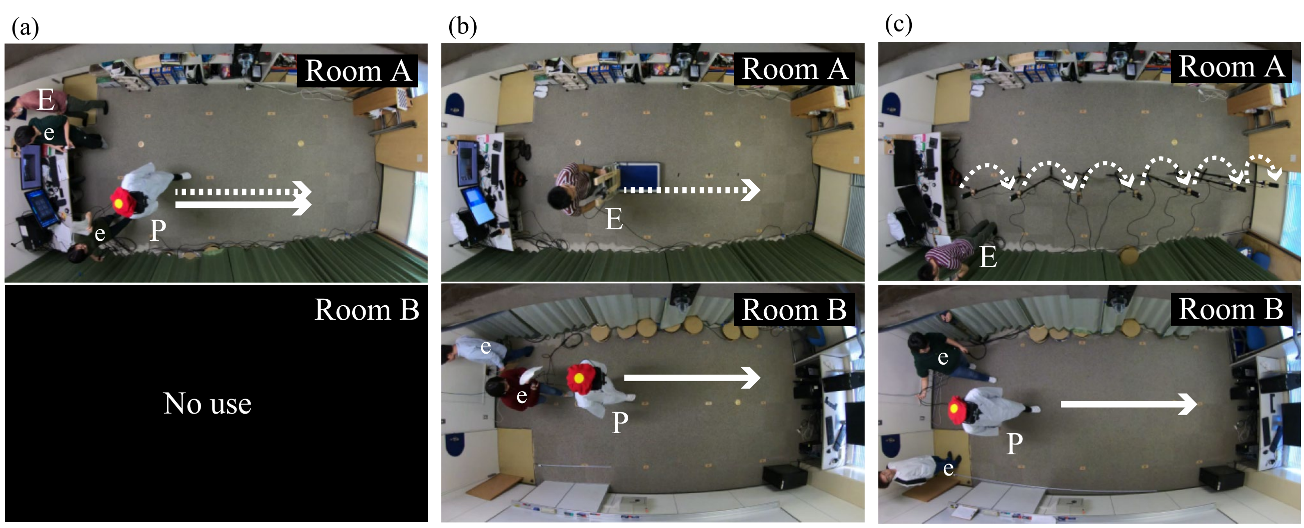

Fig. 2 Overhead views of three experimental conditions in which, in common, participants, P, wearing an HMD took six steps forward from the start position of the trial on their own timing (solid arrows). **a** Baseline condition: Participants performed trials in Room A and viewed the motion images from the camera on the HMD (dotted arrows). **b** Continuous condition: Participants performed trials in Room B and viewed the motion images from the camera on the trolley that the experimenter, E, moved in Room A according to the participant's locomotion (dotted arrows). **c** Discontinuous condition: Participants performed trials in Room B and viewed the switching images from seven cameras that the experimenter, E, controlled in Room A according to the participant's locomotion (dotted arrows). Thus, we intended to make participants visually feel as they were in Room A in all conditions. Note that the alphabet e represents the experiment assistant

images from a stereo camera (OVR VisionPro, Shinobiya.com Inc., Japan) attached to the front of the HMD are projected onto the HMD. After confirming that the participants can see their own bodies, they closed their eyes again and were instructed to perform the common protocol described in the previous section.

Continuous condition (providing invisible body and optic flow, inducing sufficient body awareness): In this condition, participants could not perceive their body but continuous motion images following their locomotion. Participants were guided to the trial starting position in Room B (Fig. 2b). Real-time images from a 360˚ camera (RICOH THETA S, Ricoh CO., Ltd., Japan) in Room A are projected onto the HMD. The camera is attached to a tripod on a trolley. The position of the camera was adjusted to the participant's eye level. Participants confirmed that their own body was visually absent despite being able to see visual scene from the position of the camera, and then closed their eyes again and were instructed to perform the common protocol. The experimenter moved the trolley straight ahead according to the participant's walk. The experimenter in Room A could see participants' walk timing by watching real-time images from a web camera installed in Room B. Thus, we intended to make participants feel as if they were performing the trial in Room A as in the baseline condition.

Discontinuous condition (providing invisible body and no optic flow, inducing insufficient body awareness): In this condition, participants wearing HMD could not perceive their body and were presented with discontinuous motion images following their locomotion. This condition was conducted in the same way as No-Body/Continuous condition except how to present the images of 360˚ camera (Fig. 2c). A total of seven 360˚ cameras, at the height of participant's eye, were placed at equal intervals starting from the trial start position in Room A. The distance from the first to the seventh device was the average walking distance of each participant, which was measured in advance under Baseline condition. The experimenter switched the images on the HMD in order 6 times at the same time as the participant's footsteps.

2.4 Measurements and analysis

We assessed the virtual presence by evaluating the subjective feeling of being-there-now, immersion, and natural walking. In addition to the subjective reports, to estimate immersion, we measured moving duration that participants performed and retrospectively reported. It has been reported that time compression effects in VR environments might arise according to subjective feeling of immersion [25]. Moreover, to estimate if participants could perform natural walking as in the base line condition, we evaluated kinematic effects of moving distance and moving path fluctuation.

To test differences between three conditions, we applied one-way ANOVA and post hoc comparisons with *t* test corrected using extended Bonferroni procedure [26] to obtain data below. The significance level was set at $p < .05$. Data were analyzed with statistics software (R, The R Foundation for Statistical Computing, Vienna, Austria).

Subjective ratings: A questionnaire consisting of six statements was administered. The items (translated from Japanese) were as follows: (1) "I felt that I was actually in the room projected on HMD.", related to the feeling of being-there; (2) "I felt that the scene I saw was pre-recorded one.", related to the feeling of being-now; (3) "I felt that my walking moved the viewpoint.", related to body awareness; (4) "I could walk as usual."; (5) "I felt that something in the room changed during trials." Participants indicated their responses on a visual analog scale with the seven guides arranged at equal intervals ranging from − 3 (strongly disagree) to + 3 (strongly agree).

Moving duration: Actual moving duration was recorded by the experimenter using a stopwatch in each trial. Reported moving duration was retrospectively estimated by participants using a stopwatch immediately after they finished walking in each trial. As for both measures, the average of 10 trials was used as data for each condition.

Moving distance: Moving distance from the start position to the goal position, i.e., actual moving distance, was recorded by the experimenter using a tape measure in each trial. Also, distance from the estimated start position, where participants returned at the end of each trial, to the actual start position, i.e., replicated moving distance, was recorded by the experimenter using a tape measure. As for both measures, the average of 10 trials was used as data for each condition.

Moving path fluctuation: Participants' movements were recorded by a video camera (GoPro Hero6, Woodman Labs) installed near the ceiling of the experimental room (height above the floor: 2993 mm). From the video images, participants' positions on the floor, represented by the center of both feet, were extracted at three frames per second. The origin of coordinates was set to the start position, $(x, y) = (0 \text{ cm}, 0 \text{ cm})$. The x-axis was set to the straight line passing through the start and goal positions. Then, a mean squared error (MSE) of y between x-axis and the moving path was calculated as moving path fluctuation in each trial. The average of 10 trials was used as data for each condition.

3 Results

3.1 Subjective ratings.

We found that there were significant differences among conditions for item 1, 2, and 3 and not in item 4 and 5 (Fig. 3), item 1: $F(2, 22) = 8.47$, $p < .01$, $\eta^2 = 0.44$; item 2:

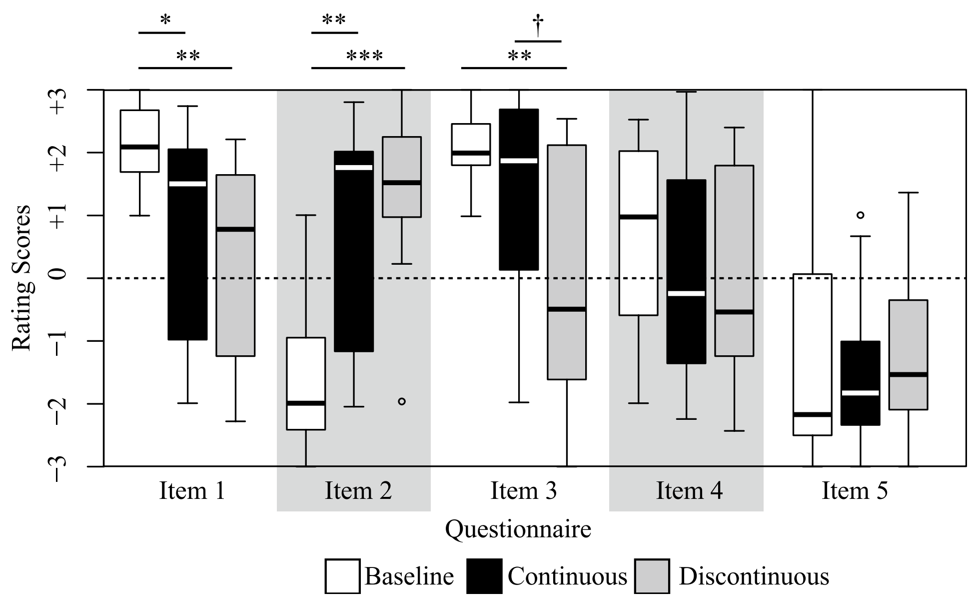

Fig. 3 Rating scores of subjective feelings. Box-and-Whisker plots represent the median of the data (thick lines), data between the first and third quartiles (boxes), and the maximum and minimum data (whiskers). Open circles show outliers. Asterisks (daggers) indicate the (almost) statistical significance in terms of post hoc test ($^{\dagger}p<.10$; $^{*}p<.05$; $^{**}p<.01$; $^{***}p<.001$)

$F(2, 22)=14.32$, $p<.001$, $\eta^2=0.57$; item 3: $F(2, 22)=6.85$, $p<.01$, $\eta^2=0.38$; item 4: $F(2, 22)=1.07$, $p=.36$; item 5: $F(2, 22)=0.12$, $p=.88$. Item 1, representing the feeling of being there, showed that the score of Continuous and Discontinuous conditions is significantly lower than that of Baseline condition, Baseline versus Continuous: $t(11)=3.01$, $p<.05$, $d=0.87$; Baseline versus Discontinuous: $t(11)=3.90$, $p<.01$, $d=1.12$; Continuous versus Discontinuous: $t(11)=1.13$, $p=.28$. Item 2, representing the feeling of being in the past, showed that the score of Continuous and Discontinuous conditions is significantly higher than that of Baseline condition, Baseline versus Continuous: $t(11)=3.78$, $p<.01$, $d=1.09$; Baseline versus Discontinuous: $t(11)=5.39$, $p<.001$, $d=1.55$; Continuous versus Discontinuous: $t(11)=1.03$, $p=.32$. Item 3, representing the feeling of self-motion, showed that the score of Discontinuous condition is (almost) significantly lower than that of Baseline and Continuous conditions, Baseline versus Continuous: $t(11)=1.35$, $p=.21$; Baseline versus Discontinuous: $t(11)=4.05$, $p<.01$, $d=1.17$; Continuous versus Discontinuous: $t(11)=2.05$, $p=.06$, $d=0.59$.

3.2 Moving duration.

We found that there were significant differences among conditions for actual moving duration and reported moving duration (Fig. 4), Actual moving duration: $F(2, 22)=6.58$, $p<.01$, $\eta^2=0.37$; Reported moving duration: $F(2, 22)=3.97$, $p<.05$, $\eta^2=0.27$. Actual moving duration showed that the time of Continuous and Discontinuous conditions is significantly higher than that of Baseline condition, Baseline versus Continuous: $t(11)=4.06$, $p<.01$, $d=1.17$; Baseline versus Discontinuous: $t(11)=2.72$, $p<.05$, $d=0.78$; Continuous versus Discontinuous: $t(11)=1.14$, $p=.28$. Reported moving duration showed that the time of Discontinuous condition almost significantly higher than that of Baseline and Continuous conditions, Baseline versus Continuous: $t(11)=0.19$, $p=.85$; Baseline versus Discontinuous: $t(11)=2.07$, $p=.06$, $d=0.60$; Continuous versus Discontinuous: $t(11)=2.78$, $p<.05$, $d=0.80$.

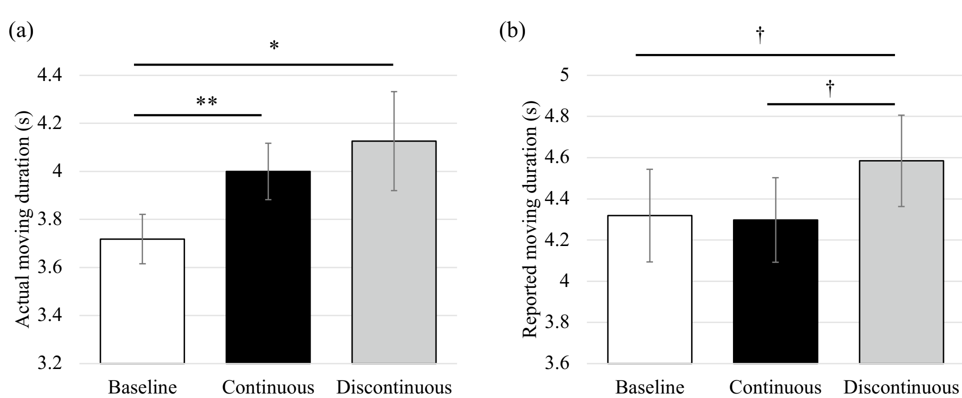

Fig. 4 Results of moving duration: the actual moving duration (**a**) and the reported moving duration (**b**). Error bars represent the standard error. Asterisks (daggers) indicate the (almost) statistical significance in terms of post hoc test ($\dagger p<.10$; $*p<.05$; $**p<.01$)

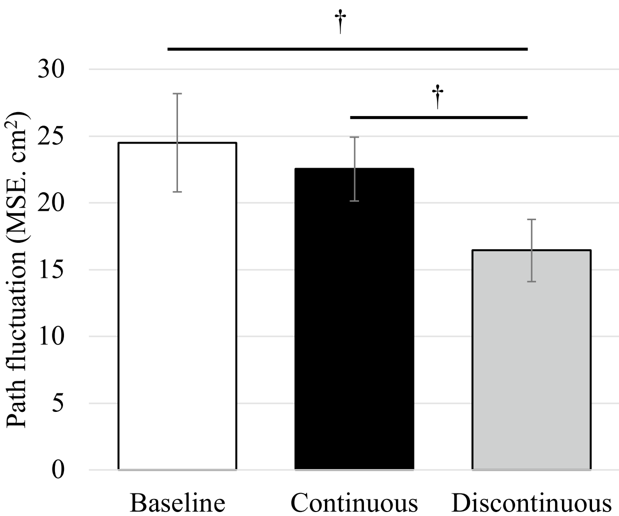

Fig. 5 Results of path fluctuation. Error bars represent the standard error. Daggers indicate the almost statistical significance in terms of post hoc test ($^{\dagger}p < .10$)

3.1 Moving distance

We found no significant differences among conditions for actual moving distance and replicated moving distance, Actual moving distance: $F(2, 22) = 2.40$, $p = .11$ (Baseline: 324.9 ± 47.2 cm; Continuous: 347.7 ± 56.1 cm; Discontinuous: 339.9 ± 60.8 cm); Replicated moving distance: $F(2, 22) = 0.05$, $p = .95$ (Baseline: 74.6 ± 27.9 cm; Continuous: 73.6 ± 28.5 cm; Discontinuous: 75.3 ± 24.3 cm).

3.2 Moving path fluctuation

We found that there was significant difference among conditions for path fluctuation (Fig. 5), $F(2, 22) = 5.34$, $p < .05$, $\eta^2 = 0.33$. Path fluctuation showed that the MSE value of Discontinuous condition is almost significantly lower than that of Baseline and Continuous conditions, Baseline versus Continuous: $t(11) = 0.80$, $p = .44$; Baseline versus Discontinuous: $t(11) = 2.78$, $p = .05$, $d = 0.80$; Continuous versus Discontinuous: $t(11) = 2.62$, $p = .05$, $d = 0.76$.

4 Discussion and conclusion

This study explored the effects of body awareness tuned by visual presentation, while users move their viewpoint by voluntarily walking, on virtual presence in a camera-image VR environment. In comparison with the baseline condition close to the real environments, losing visual body per se decreased the feeling of being-there-now, as indicated by questionnaire items 1 and 2, unlike our expectations. However, in the continuous condition, participants reported the same level of moving duration with the baseline despite difference in actual duration, and also showed the same level of path fluctuation with the baseline. Therefore, providing continuous optic flow to induce sufficient body awareness in VR maintained virtual presence equivalent to the baseline in terms of immersion and natural walking, as opposed to providing discontinuous flow. Additionally, the lowest score on item 3 asking the sense of agency supported an induction of insufficient body awareness in the discontinuous condition. Scores on item 4 and 5 indicated that there were no differences in effects of wearing an HMD on subjective walk experience and in recognizing the environments, respectively. Moreover, the results of moving distance suggest that voluntarily walking could maintain distance feeling.

Optic flow itself can induce the perception of self-motion [27]. In the Continuous condition of our study, participants' viewpoint continuously moved in accordance with their physical movements. Therefore, visually induced self-motion could be consistent with the actual motion, suggesting that this kind of consistency is likely to provide to some extent the reality of walking motion, referred to as the sense of agency [22], regardless of visibility of one's body.

The strong feeling of body-ownership might need some object as a reference [18]. Therefore, there is a possibility that the absence of a reference in our study decreased the feeling of body-ownership and declined the feeling of being-there-now. However, positive average responses to questionnaire item 1 still suggest that the feeling of being-there is likely to be maintained even though the body is visibly lost.

VR has an advantage of being able to ignore physics in everyday life. Therefore, the reality emerging in VR environment should have unexpected aspects. Providing unusual perception, as in an invisible body and a discontinuous optic flow in this study, would be necessary to discover the reality of VR experience from different perspectives. Because this study focused on the body awareness tuned by visual presentation, an experimental condition involving visible body and discontinuous flow was not examined. Comparisons among four conditions would be necessary to reveal effects of visual presentation itself.

Data availability All data are available from the corresponding author upon reasonable request.

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