Acquisition of the Width of a Virtual Body through Collision Avoidance Trials

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SUMMARY The progress of immersive technology enables researchers and developers to construct work spaces that are freed from real-world constraints. This has motivated us to investigate the role of the human body. In this research, we examine human cognitive behaviors in obtaining an understanding of the width of their virtual body through simple yet meaningful experiments using virtual reality (VR). In the experiments, participants were modeled as an invisible board, and a spherical object was thrown at the participants to provide information for exploring the width of their invisible body. Audio and visual feedback were provided when the object came into contact with the board (body). We first explored how precisely the participants perceived the virtual body width. Next, we examined how the body perception was generated and changed as the trial proceeded when the participants tried to move right or left actively for the avoidance of collision with approaching objects. The results of the experiments indicated that the participants could become successful in avoiding collision within a limited number of trials (14 at most) under the experimental conditions. It was also found that they postponed deciding how much they should move at the beginning and then started taking evasive action earlier as they become aware of the virtual body.

key words: body ownership, embodiment, body width, virtual reality, avoidance behavior

1. Introduction

Information technology, and particularly immersive technology, enables researchers and developers to build work spaces that are freed from real-world constraints. Users can easily undergo changes to their body in size and build and shapeshift into any animal or item within the immersive spaces. The same applies to tele-existence systems at which a human operator performs remote manipulation tasks with the use of a mechanical robot. In the human-computer interaction viewpoint, humans interact with the virtual or remote environment through their avatar, which has a body regardless of the type of the implementation (graphical or physical form), but an avatar’s body is not seen in most cases. We wonder whether and how the user becomes aware of the body.

It is noted here that behavior of the users is changed by the characteristics of their body. This phenomenon has been recognized and is known as the Proteus effect [1]. Similarly, a theory of embodied cognition (EC) has been studied so far [2]. It holds that cognition cannot be explained by brain operations alone and occurs with reference to a broad range of facts about the body and its relationship to an environment; to summarize, the body shapes the mind [3]. The concept of body image and body schema (BIBS) has been discussed in connection with EC. In brief, body schema is the unconscious motor and postural control of one’s own body, while body image is the perception of one’s own body in the mind. In addition to offering theoretical frameworks for human cognition, EC and BIBS have great potential to offer a practical solution to problems in fields such as manufacturing [4] and robotics [5].

Although numerous studies have been performed on the influence of the body on perception, these studies considered the body to be simply scaled up or down (e.g., adult or child) [6], [7]. In other words, the ratio between the width and the height did not change in these studies. This does not provide an exhaustive treatment of this question as illustrated the following scenarios: Consider walking on a street in a crowded city. You would take care not to bump into someone or something by maintaining an appropriate distance. Interestingly, you can do it without any difficulty. This is because you already have your BIBS. Then, what will occur when the body is augmented by extra arms or a tail that is becoming a reality? Can you walk on the street as before? Another example concerns telepresence robots, or MRP (mobile remote presence) systems [8] that comprise a video/audio communication unit connected to a wheeled base. They make it possible for the user (also known as a pilot) to engage in social interactions with people in the distance. The pilot needs to clear people and objects nearby when he/she moves. The robot has a stick shape in many cases, and its width can be smaller than human body width. In fact, the width of Double 3 mobile remote presence system is only 10 inches.

In this paper, we examine human cognitive behavior through simple yet meaningful experiments using virtual reality (VR) as a step toward exploration of mechanisms of obtaining the sense of body ownership. Two experiments were conducted, in which participants were modeled in an immersive virtual space as a board having a certain width, where the board is not seen. In the first experiment, a spherical object approached the participants to assist them to understand the unseen body (board). When the object hit the board, it generated a sound at the contact point through a pair of earphones attached to a head-mounted display (HMD) along with certain visual effects. The first experiment we performed was to test how precisely the participants perceived the virtual body (width). In the second experiment, we

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examined how the body perception was generated and changed as the trial proceeded when the participants tried to move right or left actively for avoidance of collision with the flying object. The results of this experiment indicated that the participants could become successful in avoiding collision within a limited number of trials (14 at most) under the experiment setting. It was also found that they postponed deciding how much they should move at the beginning and then started taking evasive action earlier as they become aware of the virtual body.

The remainder of this paper is organized as follows: In Sect. 2, works related to the present study are described. Section 3 described our motivation for this research. In Sects. 4 and 5, the experiment is presented with a detailed analysis of human behaviors. A discussion of the results of the experiment is presented in Sect. 6. Finally, Sect. 7 concludes the present work.

2. Related Work

2.1 Body Illusion and Embodiment

A major subject of study in neuroscience underlying body perception and self-consciousness is body ownership illusion (BOI). Rubber hand illusion [9] is the most famous example, in which the feeling of ownership of a rubber hand displaced from one’s own occluded hand is induced by giving a synchronous stroke to both hands. Martin et al. investigated replacing body parts with digitized unnatural objects such as whiskers and hammers to understand how humans perceive their body and its operations [10]. In addition, out-of-body experiences, which are a sensation of one’s consciousness leaving one’s body [11], can be linked to BOI and have received wide attention by not only neuroscientists and philosophers but also computer scientists/engineers [12], [13]. Other related studies revealed that people could experience the full body-swapping illusion [14].

While (parts of) the body is presented to participants in the process of illusory experiences in most of the studies, this must not always be the case. It has been reported that an illusion can arise even when participants do not see their body. This entire invisible body ownership illusion can be induced when the participants observe a paintbrush moving in an empty space, while receiving simultaneous touches on the corresponding parts of their hidden real body [15]. Kondo et al. [16] reported that hands and feet were sufficient to induce the illusion, and the effect was as strong as that when using a whole-body avatar. Lugrin et al. [17] examined the effect of varying the number of visible body parts of an avatar on player experience and performance in VR game play. Furthermore, it has been investigated that multisensory integration processes of bodily self-consciousness do not require conscious awareness of the sensory stimuli [18]. It is widely understood in the body perception and self-consciousness field that the sense of self is not hardwired but can be easily changed.

Embodying an unnatural sized body often happens in VR. Importantly, the size of a virtual body influences the perceived size of virtual objects [6], [19]. Participants perceived objects to be larger when they experienced the small body illusion, and vice versa. It was also reported that this effect was specific to the virtual (one’s own) body rather than another familiar-sized object [19] and there is a greater overestimation in the case of small-body illusion compared with the case of large-body illusion [20]. Recent research also revealed that when the participants interact with objects using virtual hands, the size of the objects influences the perceived size of the hands [21].

2.2 Application-Oriented Trials with Body Perception

Researchers in the field of human-computer interaction have been actively studying augmentation and amplification of human perception in order to enhance existing human abilities or create new capabilities in specific applications [22]. Piumsomboon et al. [7] explored two embodiment techniques named “superman” and “giant” as an interface to flying telepresence for multiscale mixed reality remote collaboration. The superman metaphor retains the user’s real-world scale and the user feels as though he is flying high above, while the giant metaphor enables the user (avatar) to be scaled and the user feels him/herself watching from above. OutsideMe is an external self-image mixed reality system for dancers. They can observe themselves from the perspective outside their body while they are practicing [13]. Fan et al. [23] presented a multi-embodiment interface for ergonomic product design in which additional simulated virtual bodies are superimposed on the user’s own body. The idea of controlling the size of people meeting face to face is presented in [24], aiming to reduce the discomfort caused by inappropriate interpersonal distance and thus enable a comfortable social life. It has been experimentally researched that the size of interpersonal space is affected by manipulation of one’s own body representation [25], while our study aims to uncover the mechanisms of acquiring the (extended) body width when it differs from ours. Medeiros et al. [26] examined how the perspective from which the avatar is viewed (either first- or third-person) affects embodiment and task performance in navigation tasks.

2.3 Augmentation and Telepresence of Physical Body

Physical body augmentation is another active research issue in connection with embodiment [27]. Extra body parts installed on the body include arms [28], [29], fingers [30], [31] and tails [32], [33]. Furthermore, immersive technology enables engineers to intentionally extend certain virtual body parts such as arms and fingers to expand the accessibility in space. For example, Feuchtnet et al. [34] presents an interaction technique in which the user’s arm is extended in augmented reality to allow him/her to manipulate a device that is out of reach, while preserving the perception that the artificial arm is actually part of his/her own body. Similar ideas
of extending the length of a user’s hand were presented in [35], [36]. Ogawa et al. [37] presented the idea of stretching fingers, called Metamorphosis Hand, to have the interactive experience of playing a virtual piano.

Meanwhile, MRP systems are considered an extension of the pilot’s body. Several systems are on the market now, which include Double 3, VGo, Texai, QB and newme. Since they move around in a remote environment, avoiding obstacles is obviously an important feature [38]. Though several systems have support mechanisms of detecting obstacles and avoiding collisions with the obstacles [39], it is still important for the pilot to have control over the behavior of the systems to fully leverage human capabilities.

An appearance of the MRP systems is quite different from the human, but a certain type of robots called an android or geminoid is designed to resemble the human. It has been reported that BOI is invoked so that the user (operator of a robot) receives a feeling of being poked when someone pokes the robot in the distance [40]. As an extension of the result, investigation of how the presence of agency impacts one’s body ownership is presented in [41].

### 2.4 Perception of Space and Motion

Knowing that animals need to sense danger in an attack in order to survive in their environment, numerous studies on the potential information that can be used to anticipate impending collisions have been performed over the past few decades. One important indicator in the trials is time-to-collision or time-to-contact (TTC), which is defined as the time remaining before contact between the observer and an object (enemy) [42], [43].

TTC can be obtained simply by visual image processing, without the detection of depth-oriented information such as distance and velocity [43], [44]. While most of the previous studies dealt with rigid objects, some assumed semirigid objects such as pedestrians as obstacles [44]. Furthermore, the feasibility of TTC has been proven in industrial applications such as vehicle control [45], [46].

Perception of egocentric distances is another perspective. Generally, distance perception may be influenced by not only depth cues but also environmental context and personal variables such as the physiological state or the intention to act [47]. In addition, researchers have conducted studies on the perception of egocentric distances in virtual environments [47], [48]. It has been well-established that when participants experience a virtual world through HMD, distances are underestimated compared to the distances in real environments.

Our work differs from the abovementioned studies in that we explore human’s cognitive behavior of his/her body width assessment based on the spatial relationship between the self and the reference object.

### 3. Our Motivation for This Research

Body size estimation has been a research field of great interest for psychologists and clinicians because of its impact on our psychological health and social behavior. It is concerned with bodily self-consciousness. Our study differs from such studies in that we are interested in user’s interaction behavior with their surroundings.

Let us give one example scenario. The body can have another or extended body with the aid of instruments such as a car or a robot, but the extended body may not be directly identified by the user, as conceptually depicted in Fig. 1. The same is true if the user immerses in the VR space to walk through. In order to have better operation results, the user needs to grasp his/her extended or virtual body, or BIBS.

This trends raise a research question: How accurate and quick do users capture the width of their unseen extended body (human-operated machine) and get used to it? As the first step toward helping engineers develop truly operable machines that work as integral parts of users’ bodies, this paper attempts to explore how bodily perception is shaped in a VR space through the task of collision detection. This study will offer a further contribution to the development of real industrial products.

### 4. Experiment 1

We first tested how precisely the participants obtained the sense of a virtual body (width) as a baseline for the experiment. The participants were modeled as a board in our experiments. Here, the board is not seen by the participants and its width is not specified. To assist the participants to perceive the unseen body (i.e., board), a spherical object was thrown at them, as researchers have explored the perception of impending collision between the self and approaching objects (e.g., [49]). When the object hit the board, it generated a sound at the contact point through a pair of earphones attached to a head-mounted display (HMD), as well as certain visual effects that will be described below.
4.1 Participants, Apparatus, and Procedure

Eight participants (6 men and 2 women) aged 21–60 years (average: 38.5, standard deviation: 13.9) participated in the experiment. They had normal visual sensations and physical ability. All of the participants gave consent after receiving a full explanation of the test procedure (Appendix A shows the task specifications).

The computer used in the experiment was equipped with an Intel Core i7 (3.50 GHz), 16 GB of RAM, and an NVIDIA GeForce GTX 1080 graphics card. The virtual scene was presented to the subject through an Oculus Rift HMD (CV 1) with a resolution of 1080x1200 pixels per eye. The field of view (FOV), the refresh rate, and the weight of the HMD were 110 degrees, 90 Hz, and 470 g, respectively. The virtual environment of the experiment was implemented using the Unity 5.6.0f3 (64-bit) platform.

Two board (body) widths were employed for the experiment: 0.2 m (Type A) and 0.7 m (Type B). These two board widths were determined to be smaller in Type A and larger in Type B, based on the human body width. The diameter of the spherical object was 30 cm. It was launched from 10 m away and in front of the participant, and reached the participant within approximately 1.3 s (see Fig. 2) at a speed of 7.5 m/s. The object was thrown randomly within a range of ±2° for Type A and ±4° for Type B. These ranges were determined in a trial-and-error manner at a preliminary session so that the contact rate not much would change. The object was launched from a height of 1.0 m above the floor and reached the board at a random height from 1.2 m to 2.0 m above the floor, as illustrated in Fig. 3. The reason for fixing the object launching position to one is that we aimed to help participants focus on understanding the width of the board, in the same way as in many TTC studies. Figure 4 shows a view that was provided to the participants. Several spherical object images are illustrated in the figure for reference; however, in reality, only one object image was displayed with its shadow on the floor. In addition, the dashed line indicating the starting point of the object was not displayed in the actual application.

As a visual effect helping the participants to identify the collision of the object, the background was shaken in both rotational and back-forth directions (see Fig. 5). The rotational effect caused the background to be shaken in the direction of the rotation. The effect of this motion became greater as the object hit the board farther away from its center, but there was no visual change when the object hit the center of the board. That is why the back-forth effect was combined with the rotational effect. In the back-forth effect, the background image was shaken back and forth, regardless of the contact position. In addition, the sound of contact was generated at the contact point through a pair of earphones attached to the HMD device when the ball hit the board.

As the participant’s head moved, the VR images changed. However, the position of the board did not change in the VR space from its initial position and was kept unchanged unless it came into contact with the object.

The subjects were divided into 2 groups: half of the subjects (Group 1) experienced Type A first, then Type B, and for the other half (Group 2), the reverse procedure was followed. In each trial, the object was thrown 60 times.
After the completion of each trial, we asked the participants to gesture how wide they thought the board was by extending their hands apart, and we measured the length between their hands. Although there are various measurement methods [50], we adopted this method because it was a simple and easy way for participants wearing an HMD to externalize the extended body (board) width.

4.2 Results

For Type A, participants estimated 0.38 m (SD: 0.13 m), and for Type B the estimate was 0.63 m (SD: 0.11 m). The estimated board width for Type A was wider than the actual board width, whereas for Type B it was narrower.

5. Experiment 2

In the next experiment, we examined how the sense of body ownership was generated and changed as the trial proceeded when the participants tried to move right or left actively for avoidance of the collision with approaching objects.

5.1 Participants, Apparatus, and Procedure

Fourteen subjects (11 men and 3 women) aged 22–24 years (mean: 22.6, standard deviation: 0.73) participated in the experiment. Some of them had participated in Experiment 1, and we therefore took a 3-month break between the experiments. They had normal visual sensations and physical ability. All of the participants gave consent after receiving a full explanation of the test procedure (Appendix B shows the given task specifications).

We employed the same computing equipment as that used in Experiment 1. In addition, to detect the participants’ avoidance motion to the right or left, we utilized Microsoft Kinect V2 with a Unity package (Kinect.2.0.1410.19000). Kinect was installed facing the participant, placed 0.75 m above the floor with reference to the center of the RGB camera (see Fig. 6). The subject stood at a distance of 1.5 m from the device in front of its RGB camera. The participant’s position was set at the chest center (spine shoulder). All of the participants never deviated from the sensing area during the trials.

We used the same stimulus setting as in Experiment 1. Meanwhile, to simplify the experimental setup and focus on the participants’ behavior, Type B (0.7 m) was chosen for the width of the board because its standard deviation was slightly lower than that of Type A. Furthermore, considering that it is not easy to quickly move the body, we decided to reduce the speed of the sphere object to 5 m/s. The height of the moving object was kept constant and the direction of the object on a horizontal plane ranged within ±3°. Moreover, the object was alternately thrown to the right and left with the purpose of encouraging the participants to try to identify the board (body) width.

In addition, the participants were informed about the remaining duration of the trial. For this purpose, the participants were shown 2 status bars indicating durability and energy. The durability value was in the range from 0 to 100 and decreased each time an object hit the body. When the durability became zero, the trial was completed. The energy value decreased according to how much the participant moved during the trial. When the energy value became zero, the trial was completed. Here, the durability goes to zero after 25 contacts and the energy goes to zero after moving 50m in total. Because of these durability and energy constraints, the participants were encouraged to effectively avoid the flying object while seeking to estimate the body width.

The trial continued for up to 100 incoming objects, unless the durability or energy ran out. A time series dataset of the movements of the participants during the trials and the object trajectories were recorded for analysis.

5.2 Results

None of the participants completed 100 trials. The mean number of trials conducted per participant was 53.6. The total number of trials of all of the participants was 750; the maximum number of trials per participant was 71 and the minimum was 24. The standard deviation was 10.7. In the following, we analyze the experimental results in terms of the distance between the object and the board and the progress of a trial.

5.2.1 Proximity Distance

Figure 7 is a histogram of the distance between the center of the board (body) and the passing/hitting point when the object reached the board, which we call the proximity distance. This proximity distance variable is 0.5 m, the sum of half the board length (0.35 m) and the object radius (0.15 m) when the object only touches the right side of the board when the participant moves to the left (left shift). On the other
hand, the proximity distance is $-0.5$ m when the object just touches the left side of the board when the participant moves to the right (right shift). If the proximity distance is greater than 0.5 m or less than $-0.5$ m, it indicates that the participant (board) succeeded in avoiding the object. Conversely, values between $-0.5$ m and 0.5 m indicate that the board and the object were in contact.

An ANOVA found that there was no significant difference in the mean proximity distance (absolute value) between the right shift group and the left shift group ($F(1, 748) = 0.23, p > 0.05$). The mean value was 0.60 m (SD: 0.26 m). This means that the width of the board perceived by the participants was 0.90 m, because the board width should have the proximity distances of 0.60 m in both right and left directions and the size of the ball needs to be subtracted for the calculation of the board width; that is, $0.60 \times 2 - 0.15 \times 2$.

5.2.2 Avoiding Timing

To identify any trends in the variance of the avoidance behavior in a trial, we define the avoiding timing as the amount of the participant’s lateral movement from the moment when the object appears until it reaches the first half of the travel distance (i.e., 5 m) divided by the total lateral movement in one trial. The rate approaches 1 as the participant chooses his/her avoidance behavior soon after the object appears, and conversely, it approaches 0 if the avoidance behavior is postponed until the object reaches the participant.

Figure 8 shows the avoiding timing data for all of the trials; the aggregation of the trial data is analyzed separately for the right and left shifts. An ANOVA was conducted to determine the effect of moving direction with respect to the avoiding timing. The results indicated $F(1, 748) = 3.84$, $p = 0.0504$, which is close to statistical significance. Table 1 summarizes the mean and standard deviation of the avoiding timing in the right shift, left shift, and both. Given that the avoiding timing of all of the data is 0.4129 (lower than 0.5), the participants demonstrated a tendency to postpone their decision until the object was close.

5.2.3 Behavior Change as the Trial Proceeded

We investigated how the participants’ behavior changed as the trial proceeded according to the two indices mentioned above. The number of trials differed depending on the participants; therefore, the trials were divided into two groups, where a variable $k$ was used as the number of trials to be included in the first group. For example, when $k$ is equal to 3, this means that the first group includes three instances from the first to the third trial, and the second group includes the others, that is, all trials after the fourth trial. As $k$ increases by 1, the number of trial data to be included in the first group increases by 14 (the number of participants).

First, we examined whether the cognitive responses evolved as the trials proceeded by repeatedly calculating the $p$-value (probability) of ANOVA for the difference in the proximity distance between the two groups, each time changing the value of $k$. Figure 9 shows the results of evolutionary change of avoidance behavior for $k = 2$ to 20. The horizontal and vertical axes represent $k$ and $p$-value, respectively. The $p$-value is low for small values of $k$, and
it changes as the values of k become greater; therefore, it appears that there may be significant differences among the responses of the participants between the early stage (first group) and the later stage (second group). The turning point is at approximately $k = 9$.

Next, we observe concrete values of the proximity distance between the object and the body. Figure 10 shows the change in the mean of the proximity distances for all instances in the first and second groups. When the value of k is small, the mean for the trials in the first group is smaller and near 0.5 m. This means that considering that the proximity distance is 0.5 m when the object just touches the end of the board, there is a certain probability that the object will hit the participant. As the value of k increases, the proximity distance approaches 0.6 m, and the behaviors of the participants in the first group and the participants in the second group become similar. Figure 11 shows the standard deviation for a target dataset. Although the measure is rather small when the value of k is low, it increases and eventually becomes constant with a slight decrease as the value of k increases.

Figure 12 shows the transition of the $p$-values for the difference in the avoiding timing between the first and second groups. As in the case of the proximity distance, the figure shows that the $p$-value is close to zero for smaller values of k and then increases as the trials are repeated. Figure 13 shows the mean of the avoiding timing for the first and second groups. It is observed that the same pattern is created as that for the proximity distance. For the first group,
the avoiding timing increase and then reach a constant state at approximately 0.41. This indicates that in the early trials, the participants avoided the object when it approached; after a certain number of trials, the participants started taking evasive action earlier. Figure 14 shows the standard deviation of the avoiding timing. The value gradually decreases as the trials are repeated.

6. Discussion

We found that the participants successfully captured the width of the board that they could not see through trials of watching (Experiment 1) and avoiding (Experiment 2) a thrown object.

The results of Experiment 1 show that the participants perceived the body (board) width to be greater than in reality when the board width given in the trial was narrower (0.2 m), but narrower than in reality when the wider board (0.7 m) was used. This result may have been influenced by the physical size of the human body. In fact, men had an average shoulder width of 39.6 cm [51]. It is suggested that humans recognize their body in a virtual space based on their physical body in real space. Further experiments are needed by assigning different board widths.

Regarding Experiment 2, the perceived body width was 0.90 m for the 0.70 m-wide board. This result indicates that the participants overestimated the body width in contrast to the result of passive perceptual judgments (Experiment 1). The cause for overestimation appears to include a margin of error that ensures successful object avoidance under the reasonable movement penalties. If it is considered that the body width the participants had become aware was 0.63 m and was the same as that of the result in Experiment 1, the difference 0.27 m (= 0.90 – 0.63) is interpreted as the margin. It should be noted that the value is the sum of the margins on both sides and, therefore, half of this value (0.135 m) is the margin on one side. This suggests that the existence of a margin must be taken into consideration in shaping our understanding of human cognition. On the other hand, the variance in width estimation may have occurred based on whether the tasks were passive or active. There may possibly be a difference in the motor control of our body parts. In addition, the cognitive behavior may have been affected by the difference in the board width, and we will clarify the effects of the difference in size in a future study.

Meanwhile, we found that the number of trials needed for the participants to capture their virtual body was not particularly high (10–14), based on the two graph lines associated with the first and second groups for the avoiding timing in Fig. 13 becoming closer or crossing at approximately those points.

Initially, the participants were uncertain as to how wide their body (the board) was and were inclined to postpone deciding how much they should move. In other words, the participants were conservative in their avoidance behavior and maintained their position until they had to move. In addition, as indicated in Fig. 8, the timing when avoiding the object was supposed to be different depending on the movement direction. The timing of avoidance on the right side presented a slight delay compared with the left side. This may have been affected by what is referred to as the dominant eye, dominant hand, and dominant foot, or heart position (the act of protecting the heart) as a bias toward one side or the other. Since avoidance to the right side increased the risk of the object hitting the left side (heart side), the participants hesitated to move to the right. As a result, avoidance to the right was delayed compared with avoidance to the left.

Furthermore, in our experiments, the point from which the object was launched was fixed. However, there are cases where this cannot be successfully implemented in practical situations. Objects can approach from different directions. Li et al. [52] discussed the behavior of subjects responding to objects approaching at various angles of eccentricity and various speeds and showed that TTC at the initiation of the avoidance response increased for a field of vision over 20°. Further study under conditions of uncertainty regarding the direction of an approaching object is needed.

7. Conclusions

We investigated whether and how humans become aware of the width of their unseen body in a virtual space. In the experiments, the participants were modeled as a board in the space. To assist them in exploring their unseen virtual body width, a spherical object was thrown at the participants with audio and visual feedback provided when it made contact with the board.

The participants perceived the virtual body width to be wider than the actual size when the width given in the trial was smaller than the width of our physical body but perceived the virtual body with to be narrower than the actual size when a larger board was used in passive collision-avoidance tasks in Experiment 1. Overestimation of the body width was observed in active collision-avoidance tasks in Experiment 2. Participants may have taken into account a margin of error in active tasks compared with passive tasks. Further studies are needed to clarify the influence of active
and passive tasks on body awareness. Meanwhile, the investigation demonstrated that the accuracy improved with time. The number of trials required for virtual body acquisition was 14 at the most under the conditions of our experiments. It was also found that the participants tended to postpone their decision to move until the object got closer. This was conspicuous at the early stage of the trials. Then, the participants started taking evasive action earlier.

Finally, we assumed in our experiments that the board width was almost the same as the width of the human body. This may have influenced the results. An additional study with a different board width is needed, assuming that the user may shapeshift into an unfamiliar creature with a pudgy body in a virtual space or remotely operate a large machine such as construction equipment. Application-conscious studies are also necessary.

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Appendix A: Experiment 1 Task

In Experiment 1, subjects received the following explanations:

1. You are an unseen board in a VR space. You cannot see your body in the VR space. Look ahead and keep standing without moving.

2. Spherical objects will be thrown from the front one after another.

3. When the object hits the board, you will see a change of scenery and hear the sound of contact. Visual effects include rotational shock and back-forth shock. Upon rotational shock, the visual motion becomes greater as the distance to the contact point of the object from the center of the board increases. The back-forth shock is the motion that causes the background image to shake in the front-to-back direction, regardless of the contact position.

4. One trial ends when the object is thrown 60 times. Then, show us how wide the board is by extending your hands apart.

5. The trial will be repeated two times with different board widths.
Appendix B: Experiment 2 Task

In Experiment 2, subjects received the following explanations:

1. You are an unseen board in a VR space. Moreover, you cannot see your body in the VR space.
2. Spherical objects will be thrown from the front one after another. Look ahead and try to avoid the object coming toward you.
3. When the object hits the board, you will see a change of scenery and hear the sound of contact. Visual effects include rotational shock and back-forth shock. Upon rotational shock, the visual motion becomes greater as the distance to the contact point of the object from the center of the board increases. The back-forth shock is the motion that causes the background image to shake in a front-to-back direction, regardless of the contact position.
4. Two status bars indicating durability and energy are presented in the VR space. Durability decreases each time an object hits the board. If durability become zero, the trial is over. Energy decreases as you move. If energy become zero, the trial is terminated. Avoid objects efficiently while estimating the board width.
5. The trial will continue for up to 100 incoming objects.