Proprioceptive Recalibration by Moving Viewpoint: The Effect of Indirect Positional Information of Torso

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Abstract

Manipulated visual information recalibrates proprioception in which participants perceive their body parts to be at a different location from their actual position in the body. Previous studies have provided direct visual information regarding the manipulated position of the body parts, which have often been the limbs in this context. In our experiments, we manipulated the location of the viewpoint and/or the virtual right arm during the training session. The viewpoint corresponds to the position of the head, indicating the position of the trunk connected to the head. The results of the experiments showed that this indirect visual information could cause a proprioceptive recalibration of the trunk, a very fundamental body part. In addition, a comparison with the arm, for which direct visual information was provided, suggests that the recalibration of the trunk in the absence of direct visual information was weaker than that of the arm.

Keywords: Proprioceptive recalibration; direct and indirect visual information; head and limbs; virtual reality

Visual and Proprioceptive Information

The state of the body is mainly perceived through merging visual and proprioceptive information (Tsakiris, 2010). Motor training with distorted vision leads to a remapping between the positions of the body parts and proprioceptive information. This recalibration affects the later movement, purely depending on the proprioceptive information (Barkley, Salomonczyk, Cressman, & Henriques, 2014; Mostafa, Salomonczyk, Cressman, & Henriques, 2014; Mostafa, Kamran-Disfani, Bahari-Kashani, Cressman, & Henriques, 2015; Matsumuro et al., 2023).

Our experiments indicated that the adjustments in motor commands were not always necessary to the proprioceptive calibration. Namely, even if the body (limb) movements did not need to be adjusted in the training with the distorted vision, proprioceptive recalibration occurred. Additionally, in the posttraining test without visual information, the recalibrated body parts' position perception affected the body movements, merged with the actual proprioceptive information. The effect of the modified perception was stronger in the body parts where the visual information had been given in the training session.

Proprioceptive Calibration by Distorted Visual Information

The internal representation of one's body is updated continuously via the integration of various perceptual information (Tsakiris, 2010). In particular, proprioceptive information, which is afferent information collected from the body such as muscles, tendons, and joints, plays an important role in perceiving the position of the body parts (Sainburg, Ghilardi, Poizner, & Ghez, 1995; Sherrington, 2023). With this information, it is possible to understand the positional relationships among the body parts and their positions in the environment.

Many researchers have found that visual information can easily calibrate proprioceptive perception (Barkley et al., 2014; Kokkinara, Slater, & López-Moliner, 2015; Matsumuro et al., 2023; Mostafa et al., 2014, 2015; Romano, Caffa, Hernandez-Arieta, Brugger, & Maravita, 2015). The process of information integration is explained by Bayesian probability, where the more certain information is given a greater weight (Körding & Wolpert, 2004; Ernst & Banks, 2002). Without manipulation, visual information conveys the position of the body parts with greater certainty than proprioceptive information; thus, the perception of the body parts largely relies on visual information. As a result, where vision or visual information is distorted or not aligned with the real body parts, based on the visual information, proprioception is recalibrated and remapped.

For example, Barkley et al. (2014) visually added certain degrees to the angles of the participants' hand movements in a reaching task. The participants quickly adjusted their motor commands to visually touch the target, and the adjusted movements remained following the reaching task. In addition, they perceived that their hand positions were nearer to the visually manipulated position, even if there was no visual information, meaning that proprioception was recalibrated using motor command adjustments. Matsumuro et al. (2023) produced similar results with sliding both the arm and leg position 10 cm to the right, where the effect was transferred to the untrained limbs in certain conditions.

What If More Fundamental Body Parts Are Manipulated?

In previous studies, the body parts that were manipulated were limbs, including hands and feet. These parts are distant from the center of the body, and their positions are more flexible and complex through multiple joints. The torso and head are more fundamental body parts and stable, which can be the basis for considering the body parts' relationships and

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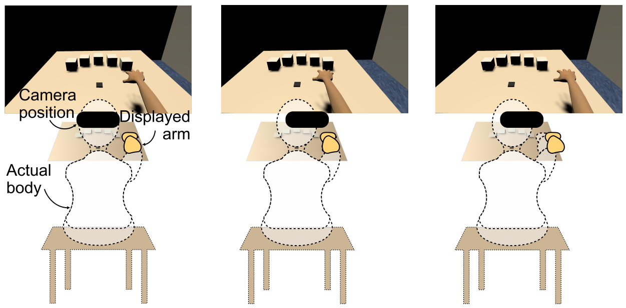
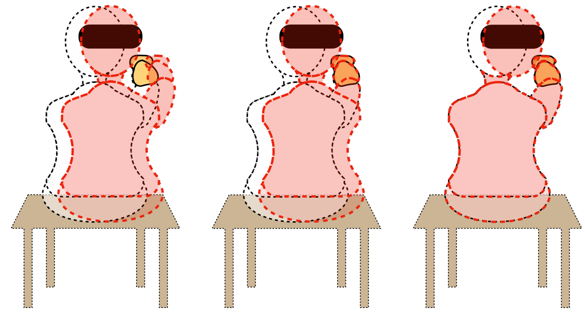


(a) Control (b) Head-only (c) Head-limb

Figure 1: Manipulation of visual information for each condition. (a) In the control condition, the positions of both the camera and the right arm were aligned with the actual body. (b) In the head-only condition, the camera position in the VR environment was located 10 cm to the right of the actual HMD position. (c) In the head-limb condition, the positions of both the camera and the right arm were at 10 cm to the right of the actual HMD and right arm position, respectively.



(a) Whole body (b) Head and torso (c) Only head

Figure 2: Predictions for the head-only condition. The red bodies present the recalibrated body. (a) Proprioception for the entire body is recalibrated, along with the head position. (b) The torso is also recalibrated in alignment with the head. (c) It is only the proprioception of the head that is calibrated.

positions. Some studies have shown that observing their body from another perspective induces an out-of-body illusion (Ehrsson, 2007; Hänsel, Lenggenhager, von Känel, Curatolo, & Blanke, 2011).

In our experiment, we manipulated the position of the head (viewpoint) to investigate whether the proprioception of a fundamental body part could be recalibrated using the first-person perspective. The participants could only observe their virtual arm from the first-person perspective. For this reason, sliding the head position was experienced as a movement of the viewpoint. Figure 1b shows the schematic image for the real and virtual bodies and the virtual head position. Figure2 describes the possible recalibrated body positions following training under the manipulation. (a) When the viewpoint movement is stronger than any other visual information, i.e., the visible virtual arm, the perception of the position of the whole body under the head, including the arm, is recalibrated following the head position. However, we did not expect that this would be true because in previous studies, the visible positional information had strong effects of recalibration (Ernst & Banks, 2002; Matsumuro et al., 2023). (b) The visible arm is perceived in the displayed position, and the entirety of the other body is perceived under the head position. (c) Only the head position is recalibrated. It is only in the case that prediction (b) is true that the perception of the positional relationship between the center of the body and the arm, measured in the post-test, differs from that of the control condition.

Is the Motor Command Adjustment Needed?

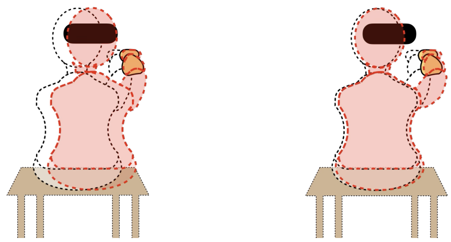
This experiment simultaneously investigated the necessity of motor command adjustments in proprioceptive recalibration. In previous studies, the visual information for the distorted position of the (body) part that was used to achieve the task was provided (Mostafa et al., 2014, 2015; Matsumuro et al., 2023). For example, when the hands were displayed 5 cm to the right of the actual position, the participant needed to move their hands further to the left than usual. In this context, what was "usual" corresponded to the unmodified proprioception; therefore, the proprioception could be easily recalibrated through this adjustment from "usual" to modified.

On the other hand, in our experiment, the relationship between the real and virtual hands and the reaching targets was the same as that in the control condition, meaning that the participants had no need to adjust their movements, even in the distorted vision condition (the head-only condition). The proprioceptive recalibration in this condition indicates that the motor command adjustment does not form a fundamental component.

Any Differences between Direct and Indirect Visual Information?

In that the perception of the positions of the parts of the body are constructed by integrating information from multiple sensors (Tsakiris, 2010), the one perceived in the post-test following the training should be based on both the online proprioceptive information and the recalibrated representation that is learned in the training, as visual information was not provided for the test. In other words, the recalibrated representation was updated or corrected near to the online proprioceptive information.

Information from each source is weighed differently depending on its degree of certainty (Ernst & Banks, 2002; Körding & Wolpert, 2004), which could be applied to the update in the post-test. The recalibrated representation was no longer supported by the online information in the post-test, and this representation was relatively uncertain compared to the online proprioception. However, the representation was nevertheless constructed in relation to the different types of information obtained during the training. For the arm, a certain position was provided as clear visual information. On the other hand, the torso position was estimated in relation to the position of the head, which was presented as the viewpoint, and no observable corresponding objects appeared in the en-



(a) Same certainty (b) Stronger for the arm

Figure 3: Predictions for the head-limb condition. The ratio of weights for the integration of online proprioceptive information and that recalibrated in the training session are (a)the same for the entire body and (b) more on the online for the torso and more on the recalibrated one for the arm.

vironment. These differences could have produced different degrees of certainty for each part in the recalibrated representation, leading to the different weights in the post-test. As another possibility, as the body forms a unitary representation, it could develop a common certainty for the whole body, once the representation was built.

We added another condition in which both the head and arm were moved from the actual position. If all parts in the body representation have a common certainty, the recalibration in the post-test could occur to the same extent for all body parts. As a result, the perceived relationship between the center of the body and the arm would be the same as that in the control condition (i.e., no significant difference; Figure 3a). If the representation of the visible part could be constructed strongly, the perception of the center of the body would rely more on the online information and significantly different behavior could be observed in the post-test (Figure 3b).

Experiment 1

The participants performed a simple reaching task in a virtual reality environment during the training session. For the first third of the session, we gradually moved the head position (in the Head-only condition) or the positions of the head and arm (in the Head-limb condition) to the right in the VR environment. No manipulation was added for the control condition. In the post-test that followed the training, the participants indicated the vertical location of the center of their body, representing their perception of the positional relationship among their body parts.

Method

Participants In all, 25 graduate and undergraduate students ($M = 21.780$, $SD = 1.488$) participated in the experiment, including 17 males and 8 females. There were 22 right-handed, 2 left-handed, and 2 ambidextrous participants, and 15 participants had experience with virtual reality.

Task and Manipulation All tasks were provided via a head-mounted display (HMD; HTCVIVE pro, HTC, New Taipei, Taiwan). The task performed in the training session was a simple reaching task. Five virtual cubes and a starting position were presented on a virtual desk in front of the participants (see Figure 1), who placed their virtual hands on the starting position. When a trial started, one of the cubes turned red. The participants virtually touched it with their virtual arms as rapidly as possible, causing the cube's color to change back to white. They then moved their arms back to the start position. These movements were tracked using VIVE Trackers. The participants repeated this reaching activity for 45 trials. The virtual arm was displayed from the elbow to the hand.

The head position and the displayed arm position differed across the three conditions. In the control condition, the head and arm were aligned with the actual position of the body position for all trials. The head position was then moved to the right for the first 15 trials in the Head-only condition. None of the other objects moved, and the virtual arm was aligned with the actual position of the right arm. The participants performed the reaching action from a viewpoint 10 cm to the right of the actual eye (HMD) position in the remaining 30 trials. In the Head-limb condition, both the head and arm positions were moved in the same manner as in the Head-only condition. The virtual arm gradually moved away from the target boxes, so the participants had to move their arms to a greater and greater degree. Figure 1 shows the schematic image of the three conditions and the participants' perspective.

Following the post-test, the HMD was blacked out, and no additional visual information was provided to the participants, who indicated the vertical location of the center of their body (represented by the belly button) using one of their limbs. To make their movements different from those in the training, the participants stretched their limbs slightly outward from the center of their body and then moved them vertically to the position that they thought was in front of their belly buttons. We did not allow them to touch the desk or the floor until they had decided on their final position. We measured the distance between the actual center of the body and the indicated location; positive values describe locations to the right, and negative values indicate the left.

Procedure At the beginning of the experiment, the participants were given a brief characterization of it, and only those who agreed with participation were enabled to continue with it. The participants received a detailed explanation of the tasks and practiced them briefly. Before each training session, the participants performed a brief task of pointing to indicated locations on the desk without the HMD to cancel the effect of the preceding condition's training. After that, the participants wore the HMD, and the positions of all the virtual objects and the camera were adjusted to align them with the actual head and right arm positions. They completed the training session in one of the three conditions. After the HMD was blacked out, a post-test was conducted with respect to each of the four limbs, in random order. The participants then responded to the five survey items using a 7-point Likert scale: (1) I felt as if the virtual right hand was my own hand (body ownership);

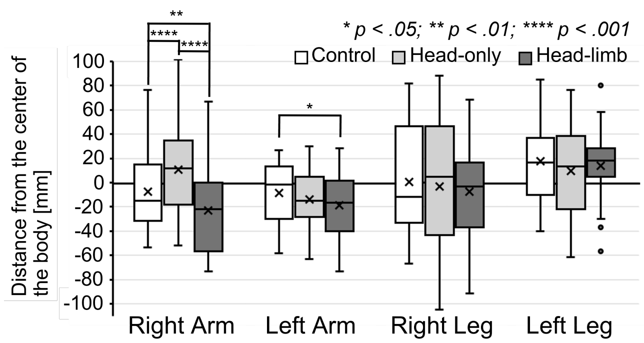


Figure 4: Distance from the center of the body in the post-test for each limb and condition in Experiment 1. Positive values indicate distances to the right and negative values indicate distances to the left.

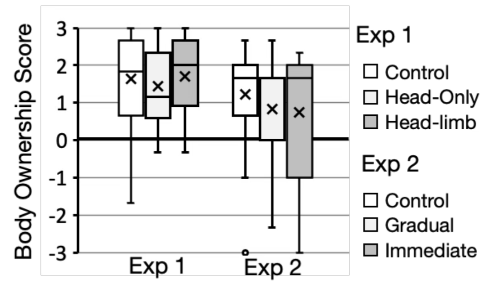


Figure 5: Body ownership score in Experiments 1 and 2.

(2) I felt as if my right hand had disappeared (dummy); (3) I felt as if my body balance was distorted (body balance); (4) I felt as if my body had become larger (dummy); and (5) The virtual hand moved just as I wanted it to, as if it were obeying my will (agency). Following the three-minute rest, the next condition was conducted.

The three conditions were conducted three times each in random order. We collected three post-test and questionnaire scores for each conditions. The scores were averaged for each limb, and questions were for each condition. After the entire experiment, we asked the participants whether they had noticed anything during the experiment to determine whether they noticed that the position of their head and/or arm had been manipulated.

Results

Three participants who had extreme scores in the control condition were excluded from the subsequent analyses. Figure 4 shows the distances from the center of the participants' bodies in the post-test. The Shapiro-Wilk test indicated nonsignificance for the data in all conditions and limbs, so we conducted a one-factor within-subjects ANOVA for each limb to investigate the differences among the three conditions.

For the scores on the right arm, we applied the Greenhouse-Geisser correction because Mauchly's test of sphericity indicated that the assumption of sphericity was violated ($W = 0.723$, $p = .039$). The main effect of the displayed positions for the head and limb positions was significant ($F(1.57, 32.89) = 29.067$, $p < .001$, $\eta_G^2 = 0.181$). Paired comparisons using Holm's method indicated a significant difference among all combinations of the three conditions: Control and Head-only $p < .001$, Control and Head-limb $p = .004$, and Head-only and Head-limb $p < .001$. The participants perceived their hands' position to be closer to the center of their bodies in the Head-only condition; by contrast, they perceived their hands to be further from the center of their bodies in the Head-limb condition.

There was a significant main effect of the conditions ($F(2,42) = 4.654$, $p = .015$, $\eta_G^2 = 0.034$) for the left arm; only the difference between the control and the Head-limb condition was significant ($p = .030$, other ps $> .116$). For both legs, the difference in the displayed positions had no significant effect (right $F(2,42) = 2.014$, $p = .146$, $\eta_G^2 = 0.009$; left $F(2,42) = 1.096$, $p = .344$, $\eta_G^2 = 0.013$).

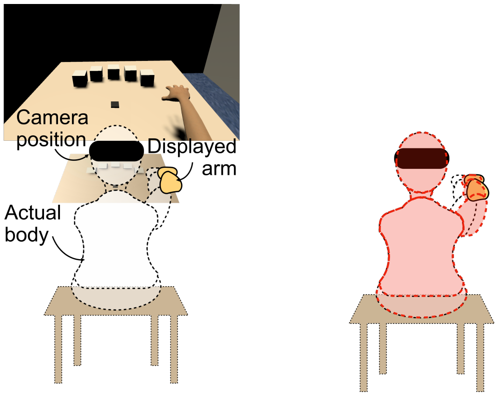
In comments following the experiment, 12 participants noted the change in their viewpoints or environments in the training session. We considered them to be those who noticed the change in viewpoint and compared them with the remaining 10. Only one participant mentioned the change in the arm position; therefore, this analysis was only performed in the Head-only condition. A 2 (control, Head-only) $\times$ 2 (notice, not-notice) analysis showed significance only between the control and head-only conditions ($F(1,20) = 32.989$, $p < .001$, $\eta_G^2 = 0.094$; notice $F(1,20) = 0.017$, $p = .896$, $\eta_G^2 < 0.001$; interaction $F(1,20) = 0.487$, $p = .493$, $\eta_G^2 = 0.002$). This means that, even if the participants noticed the manipulation of their vision, a proprioceptive recalibration had occurred that affected the following actions.

Questionnaire about Body Perception We analyzed the first, third, and fifth questions, which concerned the sense of body ownership, the distortion of body balance, and the sense of agency, respectively. We conducted a Friedman rank sum test for each question to identify the effect of the manipulations. The main effect of the condition was significant only in the body ownership question (Figure 5; $\chi^2(2) = 7.0645$, $p = .029$, $\eta^2 = 0.161$); however, the paired comparison did not show significance (ps $> .260$). In the other two questions, the change in the displayed position did not have a significant effect (χ^2s$(2) < 4.466$, ps $> .107$, η^2s < 0.108).

Discussion

Experiment 1 was conducted to answer three research questions, and these responses are given as follows.

1. The perception of the torso position could be recalibrated through the distorted visual information.
2. Motor adjustment was not necessary for the recalibration.
3. The recalibration by the positional information provided via direct visual information was stronger than that estimated from the visual information indirectly.



(a) Manipulation (b) Prediction

Figure 6: Manipulation and prediction in Experiment 2.

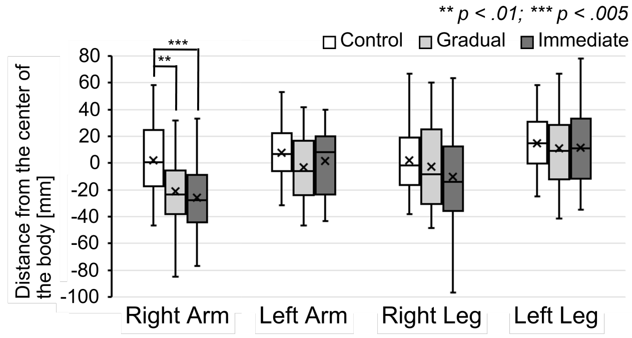


Figure 7: Distance from the center of the body in the post-test in each limb and condition in Experiment 2. The positive and negative values had the same meaning in Figure 4.

We conducted an additional experiment where we only manipulated the displayed position of the given participant's arm, as shown in Figure 6a. In the two experimental conditions in Experiment 1, the perception of the torso position was recalibrated more weakly than that of the arm, where direct visual information was provided, but this was not weak, as it was immediately recalibrated using online proprioceptive information. This conclusion could acquire more support if we could observe a greater distance from the center of the body in the additional experiment than those in the Head-limb condition in Experiment 1, as is shown in Figure 6b.

Experiment 2

We manipulated the display position of the arm in the same manner as in Experiment 1, the gradual (change) condition. We also added a condition in which the participants began the training session with the arm in the manipulated position, the immediate (change) condition, as used in the previous study. We compared these conditions to confirm that the method for changing the body parts' position did not make a significant difference. With the control condition, Experiment 2 had the three conditions.

Method

Participants

In all, 21 undergraduate and graduate students participated in Experiment 2. Their average age was 21.762 years ($SD = 0.921$), including 18 males and 3 females. Other than one left-handed participant, all participants were right-handed. All participants had VR experience.

Task, Manipulation, and Procedure

The task and post-test instruments were the same as those used in Experiment 1 and used the same procedure as that in Experiment 1.

In the gradual condition, the displayed arm position was changed gradually 10 cm to the right (Figure 6a) as it changed in Experiment 1, although the viewpoint was not manipulated. In the immediate condition, the participants began the training session in the manipulated position; namely, their arms were displayed 10 cm to the right from their actual position at the beginning of the training. The 15 trials used for the positional manipulation in the gradual condition were skipped in the immediate condition.

Results

Participants who showed extreme scores in the control condition were excluded from the analyses. The distance from the center of the body in the post-test is shown in Figure 7.

A significant effect was seen of the displayed position in the distance from the center of the body in the right-arm post-test ($F(2,36) = 12.916$, $p < .001$, $\eta^2_G = 0.165$). In both experimental conditions, the participants pointed significantly further to the right from the center than in the control condition (gradual $p = .003$; immediate $p < 0.001$). The difference between the two experimental conditions was not significant ($p = .371$). The effect of the display position was also significant for the left-arm test; however, no pair showed a significant difference in the paired comparison (control and gradual $p = .086$, other pairs $ps = .260$). The scores for the post-test for both legs did not show any significant difference ($F(2,36) < 1.904$, $p > .163$, $\eta^2_G < 0.030$).

Questionnaire about Body Perception While the manipulation showed no significant effect on the sense of body ownership (Figure 5;$\chi^2(2) = 3.0746$, $p = .215$, $\eta^2 = 0.081$), the sense of agency and body balance were significantly affected (agency $\chi^2(2) = 13.176$, $p = .001$, $\eta^2 = 0.347$; body balance $\chi^2(2) = 12.394$, $p = .002$, $\eta^2 = 0.326$).The participants felt a reduced degree of agency ($ps < .05$), and their body balances were more distorted ($ps < .05$) in the experimental than in the control conditions.

Comparison between Experiments To determine whether the result matched our prediction, we performed a 2 (control and manipulated) × 2 (Experiments 1 and 2) mixed-factor ANOVA in which the *manipulated* meant the head-limb condition in Experiment 1 and the gradual condition in Experiment 2. There was only a significant effect for the positional manipulation ($F(1,39) = 25.404$, $p < .001$, $\eta_G^2 = 0.103$), with no significant interaction ($F(1,39) = 1.610$, $p = .212$, $\eta_G^2 = 0.033$) or effect of the experiment($F(1,39) = 0.888$, $p = .352$, $\eta_G^2 = 0.004$). The Cohen's D between the control and the Head-limb conditions in Experiment 1 was 0.685, and the control and the gradual condition in Experiment 2 was 0.876. Although both showed a strong effect in the manipulation, the effect in Experiment 2 was stronger than that in Experiment 1.

Discussion

The change in the displayed arm caused proprioceptive recalibration regardless of whether the change took place gradually or was implemented from the beginning of the training session. The difference between when we only manipulated the arm position, and both the head and arm positions was not as significant as we expected. However, the larger effect size in the former condition supported our prediction.

General Discussion

We conducted two experiments to investigate proprioceptive recalibration for the head and torso relative to the arm. The results of the experiments changing the body parts, i.e., only the head, both the head and the right arm, and only the right arm, for display at the manipulated position, suggested or indicated the following three insights. Our predictions for each situation are shown in Figures2, 3, 6b.

Fundamental Body Parts Can Be Recalibrated

In the head-only condition shown in Experiment 1, the participants perceived that the center of their body was close to their arm. This indicates that their perception of their torso position was recalibrated in the training, but that of their arms was not (Figure 2b). Even where the manipulated body parts were not peripheral and the direct positional information was not provided visually, proprioceptive recalibration occurred.

This result could be observed when the participants had memorized the relationship between their viewpoint and their arm. However, if it was true, in the Head-limb condition that the identical positional relationship as that in the control condition was maintained in the training session, there could not have been a significant difference between these conditions. In the result, the significant difference from the control condition ought to be confirmed in the proprioceptive recalibration rather than in the memories of the positional relationship.

Movement Adjustment Is Not Necessarily Required

In the head-only condition, the participants performed the same movement from the beginning to the end of the training session, meaning that they performed the same hand movements as in the control condition. Without any change in the hand movements, which was often needed in the previous studies, proprioceptive recalibration occurred.

Like the proprioceptive drift seen in the rubber hand illusion (Botvinick & Cohen, 1998), recalibration could occur without body movements. However, it is important to note that these actions are not essential but are beneficial to proprioceptive recalibration. Actions are considered to be a component of evoking a sense of agency, which leads to the perception that the body is one unitary body (Borghi & Cimatti, 2010). Likewise, when the hands are moved, the information on their head and eyes is integrated to create motor commands (Henriques & Crawford, 2002); in addition, the whole body coordinately supports the hand movements (Cirstea & Levin, 2000; Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002). This unitary body perception could facilitate proprioceptive recalibration.

Indirect Positional Information May Have Weaker Effect

In Experiment 1, even where we manipulated the displayed distance in the same amount for the head and arm, the participants perceived that their arms were further from the body center than the real relation after the training session (Figure 3b). The post-test scores between the head-limb condition in Experiment 1 and the gradual condition in Experiment 2 were not sufficiently different to be statistically detectable. However, the effect size of the difference from the control condition was greater in Experiment 2. These results suggest that participants perceived the torso position to be closer to the real position than the discrepancy between the perceived and real arm position.

We consider that the lack of concrete positional information that was provided via vision (i.e., the uncertainty) could lead to unstable proprioceptive recalibration; as a result, the perception or estimation of the torso position tended to place greater weight on the online information (Ernst & Banks, 2002; Körding & Wolpert, 2004). Additionally, we cannot ignore the effect of actions performed by only their right arms. The actions increase the sense of body ownership and agency (Proske & Gandevia, 2012), and eventually, more stable recalibration. In the gradual condition seen in Experiment 2, a moderate negative correlation was seen between post-test score differences, subtracting the score in the control condition from that in the gradual condition, and the ownership ($r = -0.322$) and agency ($r = -0.316$) scores in the gradual condition. These results indicate that the participants who felt greater body ownership and agency in the virtual arm perceived their arm position as more to the right. i.e., calibrated more. Actions, including those in the torso and questionnaire concerning other body parts, can help to understand the effects of these factors.

Limitation and Future Work

TThe manipulation used in this study significantly affected questionnaire responses, particularly in Experiment 2. Compared to Experiment 1, the participants in Experiment 2 were more familiar with the HMD and VR, which may have made them sensitive to positional changes. In particular, the sense of body ownership and agency are considered to play an important role in body perception. Further investigations involving VR experiences are needed.

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