





Article

Self-Body Recognition through a Mirror: Easing Spatial-Consistency Requirements for Rubber Hand Illusion

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Abstract: Considering that humans recognize mirror images as copies of the real world despite misinterpreting optical reflections, spatial disagreement may be accepted in rubber hand illusion (RHI) settings when a mirror is used to show a fake hand. The present study performed two experiments to reveal how self-body recognition of a fake hand via a mirror affects RHI. First, we tested whether illusory ownership of a fake hand seen in a mirror could be induced in our experimental environment (screening experiment). Subjective evaluations using an RHI questionnaire demonstrated that embodiment of the rubber hand was evoked in the presence or absence of a mirror. We then examined whether using a mirror image for RHI allows disagreement in orientation (45°) between the rubber and actual hands (main experiment). The participants experienced RHI even when the actual and rubber hands were incongruent in terms of orientation. These findings suggest that using a mirror masks subtle spatial incongruity or degrades the contribution of visual cues for spatial recognition and facilitates multisensory integration for bodily illusions.

Keywords: rubber hand illusion; mirror; body ownership

1. Introduction

The rubber hand illusion (RHI) is a phenomenon in which body ownership of a fake hand is illusorily experienced when a visible fake hand and occluded veridical hand are exposed to spatially and temporarily congruent visuotactile stimuli. Since Botvinick and Cohen [1] first reported this phenomenon, the RHI paradigm has been used in studies on multisensory integration and body ownership. In this paradigm, congruency among multiple sensory cues is important [2,3]. Smaller spatial and temporal incongruity between actual and fake hands lead to more intense illusions of body ownership. For instance, when fake and actual hands are spatially incongruent (e.g., when they have different postures), the body ownership illusion is weakened [4–11]. According to Constantini and Haggard, a hand angle mismatch of 20° between the veridical and fake hands distracts from the body ownership illusion [6]. Nevertheless, this angle value varies among studies [9,12].

In experiments on the RHI paradigm, participants usually are asked to gaze at the fake hand, but visual cues are not entirely necessary to elicit an illusion [2]. In contrast, in the present study, the participants experienced RHI while gazing at the fake hand through a mirror. Under these settings,

the RHI is experienced [13–15]. Despite the reversed orientation and distant focal points, humans recognize a mirror image as a copy of the real environment [16,17]. People tend to not recognize unnatural manipulation in mirrored images such as optically incorrect tilting, compression, expansion, and left–right flipping of mirrored images [16]. Moreover, people do not accurately predict the mirror reflection and spatial relationships between the mirror and themselves [16,18,19]. Further, the locations of bodily sensations are biased or recalibrated when seen through a mirror [20,21]. This tolerance of mirrored images or spatial misallocation may robustly lead to an RHI experience in which incongruency between fake and actual hands does not disturb the illusory experience of body ownership. The present study pursues this hypothetical proposition. In one study that supports this possibility, the body ownership illusion was evoked irrespective of the egocentric or allocentric fake hand images in a mirror [14].

Three explanations are considered for the above hypothesis. First, as stated above, the perceptual tolerance to mirrored images may lead to a spatially incongruent seen hand being accepted as a part of the body. Second, using a mirror lowers the light intensity of a seen hand and facilitates the inverse effect of multisensory integration [22–24]. Third, the decrease in the reliability of visual cues may facilitate the bodily illusion experienced under a spatially incongruent condition. The decrease in visual reliability reduces the weight of the visual cues during sensory integration [25–27], which may cause the visible spatial incongruency to become less significant. We focus on whether the RHI experience is evoked using a mirror when spatial incongruency exists rather than specifying a particular aspect of the mirror images (e.g., lower reliability or weak signal level), which may moderate the spatial-consistency requirements, or discussing underlying neural bases [28–30].

In general, experimental RHI settings require careful adjustment between a seen fake hand and an unseen veridical hand such that they are spatially consistent without critical disagreements. However, such adjustment may deter the application of RHI in commercial virtual reality or augmented reality environments [31–33]. If the mirror moderates the requirement of small spatial contradiction, then the application of RHI may be extended.

In addition to using mirrors, our study features voluntary hand movement and self-generated tactile stimuli. In our experiments, the participants tapped a desktop and experienced a resultant tactile stimulus in their fingers. The voluntary motion or conjunction of the voluntary motion and self-generated tactile stimuli elicit RHI with a subjective illusion intensity that equals or exceeds the passive condition [34–38]. Voluntary motions play a significant role in forming the sense of body ownership and may facilitate the occurrence of illusion [34,36,39–41]. This study addresses the effects of a mirror on agency by considering active hand motion.

In a screening experiment, we tested whether the body ownership illusion was elicited when the participants gazed at the mirror image of a fake hand. Thus far, only one study [15] has investigated mirror-RHI involving self-generated hand motions and tactile stimuli. Therefore, this follow-up experiment is required to investigate the reproducibility of the findings of [15] in another experimental environment. The main experiment investigated whether the incongruency of the fake and actual hand postures (angles) was accepted in the RHI setting involving a mirror. The previous studies on mirror RHI did not address situations where actual and fake hands were angled.

This study was conducted with the approval of the Institutional Review Board, School of Engineering, Nagoya University (#17-12).

2. Materials and Methods

2.1. Participants

Fifteen paid university students participated in the experiments (nine males and six females; mean and standard deviation of age in years: 24 and 9.2, respectively) with written informed consent. The participants were recruited using a local advertisement poster. None of the participants had prior experience in RHI or other experiments relating to body ownership. They were unaware of the

objectives of the experiments in terms of the effects of the mirror. All participants passed the screening experiment and proceeded to the main experiment. Hence, in the main experiment, the participants were familiar with the process including how they should move their hands to effectively cause the illusory experience.

2.2. Apparatus for Inducing RHI under Self-Generated Movement

As shown in Figure 1a,b, the main components of the apparatus were a fake rubber hand, hand gloves, a cuboid frame, and a cloth that occluded each participant's right shoulder, arm, and hand. The fake rubber hand was composed of a rubber glove containing metal wires and cotton. The same rubber glove was worn by all participants. Two acrylic rods were fixed to the fake hand as shown in Figure 1c. The participants held these rods with the thumbs and palms of the right hand and moved the fake hand and their own right hands in a synchronous manner. The distance between the little finger of the fake hand and the thumb of the veridical hand was no more than 2 cm. A similar setup was used in [42].

Figure 1d shows the experimental setup involving the mirror. The mirror faced the participant at a height in the range of 15–25 cm. The distance between the participant and mirror was 50–60 cm. The spatial configuration was adjusted within these height and distance combinations, such that the participants could gaze at the fake and actual left hands in a mirror.

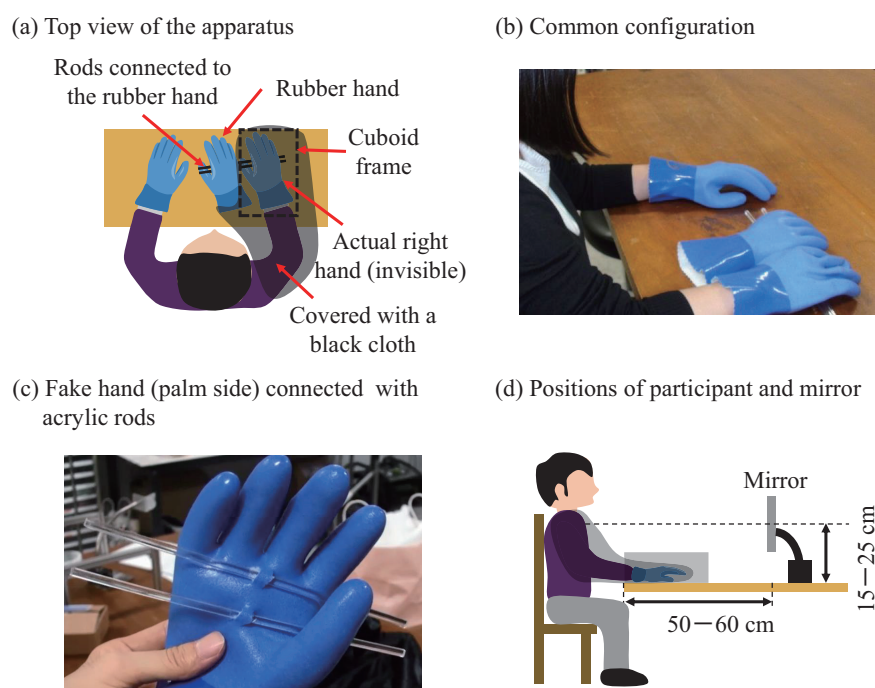


Figure 1. Experimental setups. (a) Movement of the rubber hand, which was controlled by manipulating the connected rods. (b) Common setup for all experiments. (c) Palm side of the fake hand, which was firmly supported by two acrylic rods. (d) Positions of the mirror, hand, and participant. These positions were adjusted such that the participants could see their hands in the mirror.

2.3. Common Tasks for Both Screening and Main Experiment

For the participants to familiarize themselves with the experimental setup before the main tasks, they wore rubber gloves and practiced tapping or rubbing a desktop surface while holding acrylic rods with a fake hand, as shown in Figure 1a,b. The participants tried to experience the illusion by tapping or rubbing (frontal-rear motion) the desk and chose either one or both of these hand movements to facilitate the induction of the illusion. They were instructed to select a hand movement that would allow them to experience a strong illusion. During this phase, they attempted to maintain an actual

right-hand posture as that of the fake hand. Furthermore, the fingers of the rubber hand were shaped such that the middle fingers of the actual and fake hands were at the same level and reached the desk surface simultaneously for individual participants. The experimenter monitored whether the hand positions were appropriate during the trial.

The participants experienced the illusion by moving their hands for 1 min in each trial. During the tasks, the participants tapped or rubbed the desktop with their actual middle fingertips for 1 min. They limited their hand movements (rubbing strokes or finger tapping) to a few centimeters for easier manipulation and consistency among all conditions.

In some conditions, the acrylic rods were held such that the actual and fake hands moved synchronously. This condition causes self-generated hand motion and tactile stimuli and easily evokes the body ownership illusion [15,31,35,36,38,43]. When the acrylic rods were removed from the fake hand, the fake hand remained still on the desktop, and an asynchronous condition was configured in which the actual and fake hands were independent (We call this condition the asynchronous condition, whereas in other studies, the fake and actual hands moved in a different manner (e.g., delayed) under asynchronous conditions.). In asynchronous conditions, the distance between the fake and actual right hands could be greater than that observed in synchronous conditions. The participants moved their left hands in the same manner as their right hands regardless of the synchronization of the fake hand.

The participants were instructed to gaze directly at the fake hand in the without-mirror condition (Figure 2a) and through a mirror in the with-mirror condition (Figure 2b).

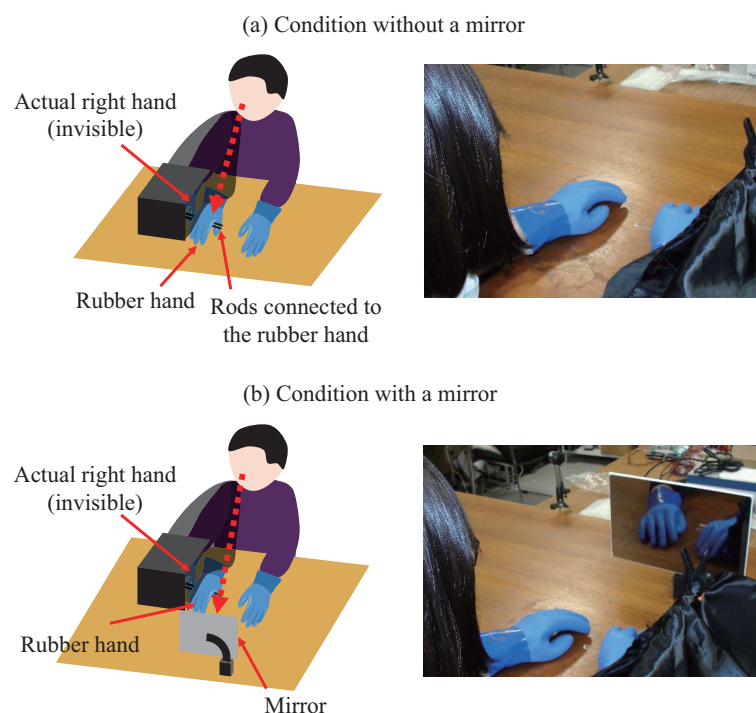


Figure 2. Experimental scene with or without a mirror. (a) Condition without a mirror in screening and main experiments. The actual right hand and arm were hidden by a box, whereas the rubber hand was visible to participants. (b) Condition with a mirror in screening and main experiments. The fake rubber hand and actual left hand could be seen in the mirror.

After each trial, the participants were encouraged to stop gazing at their hands, leave the rods, and relax such that the preceding trial would not affect the succeeding one. Notably, according to [44], the effects of RHI on excitability last several minutes in the primary motor cortex, which is longer than the inter-trial rest periods in the present study.

2.4. Screening Experiment: Follow-Up Test of Mirror RHI Involving Self-Generated Movement

We investigated whether the experience of body ownership would be evoked when the fake hand was gazed at through a mirror. The magnitudes of the illusion with and without a mirror were compared. Three conditions were applied in this experiment, as shown in Table 1. Under conditions 1 and 2, the participants held and moved the acrylic rods, and the fake and actual right hands were moved synchronously. The comparison of these two conditions may be sufficient; however, to investigate whether our experimental setup created the illusion, we introduced a baseline condition, condition 3. Condition 3 was prepared as a control, under which the fake and actual hands were separated. Although the fake hand remained still on the desk, the participants moved both their hands. The participants gazed directly at the fake hand under conditions 1 and 3, and the fake hand was seen through a mirror under condition 2. Under all conditions of the screening experiment, the fake and actual hands were aligned in parallel, as shown in Figure 3a. Each participant experienced three conditions in a randomized order in a single session, and two sessions (six trials in total) were performed for individual participants. In the paradigm of RHI experiments, the same trials are not usually repeatedly conducted because the number of conditions or stimuli is small, and the participants can memorize their answers.

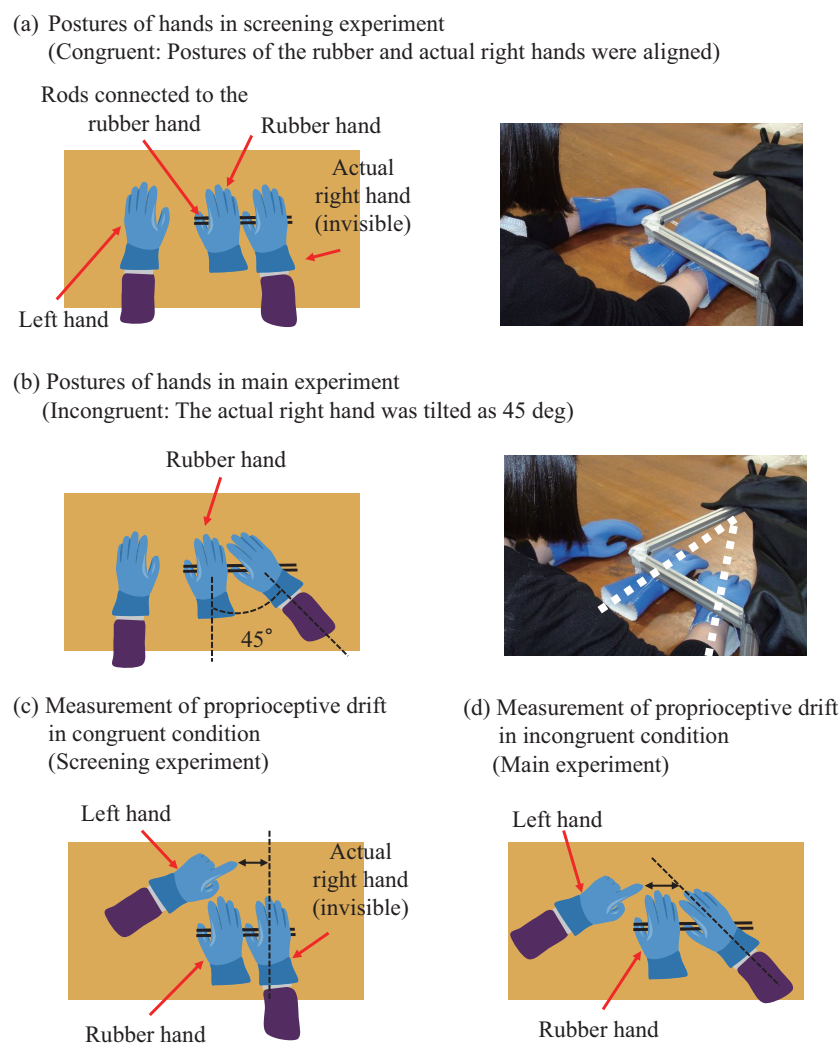


Figure 3. Actual and fake rubber hands. (a) The actual right hand was parallel with the fake hand in the screening experiment. (b) The rubber hand was tilted 45° against the actual hand in the main experiment. (c,d) The perceived finger location was measured from the longitudinal direction of the actual hand.

Table 1. Conditions in the screening and main experiments.

	No.	Condition
Screening exp. (congruent posture)	1	Synchronous without a mirror
	2	Synchronous with a mirror
	3	Asynchronous without a mirror
Main exp. (incongruent posture)	4	Synchronous without a mirror
	5	Synchronous with a mirror
	6	Asynchronous without a mirror
	7	Asynchronous with a mirror

2.5. Main Experiment: RHI under an Incongruent Hand Posture with a Mirror Image of the Fake Hand

We investigated how mirror images influenced illusory body ownership when the hand postures were spatially incongruent. Note that we did not compare congruent and incongruent conditions. Table 1 shows the four conditions tested in the main experiment. They included the combination of two factors: synchronization (synchronous or asynchronous) and the mirror (presence or absence). In all conditions, the actual hand was tilted at 45° against the fake hand (Figure 3b). Under conditions 4 and 5, the motions of the actual and fake hands were synchronized, whereas they were not under conditions 6 and 7. Similar to the screening experiment, these four conditions were tested in randomized order in a single session. In total, two sessions were conducted for each participant. In this main experiment, asynchronous conditions may not be necessary; however, as a reference base for investigating the occurrence of an illusion, we introduced asynchronous control conditions.

2.6. Modified RHI Questionnaire

The RHI experience is often assessed by the questionnaire proposed by Botvinick and Cohen [1]. We added questionnaire items regarding agency [37,45] and modified some statements to fit our RHI setting. After each trial, the participants responded to the six questionnaire items shown in Table 2. These items were provided in plain English. Each item was rated using a seven-point scale (−3: I disagree with the statement, to +3: I agree with the statement). Q1 (body ownership) and Q2 (agency) concerned the illusory experience of RHI, whereas the others were prepared as controls for the body ownership statement. Other possible questionnaire items include queries about disembodiment [46,47], which were not used in the present study.

Table 2. Questionnaire for the subjective evaluation of RHI (modified from [1]).

Q1	I felt as if the seen rubber hand was my hand.
Q2	It seemed that I was directly moving the seen rubber hand.
Q3	It seemed as if I might have more than one right hand or arm.
Q4	It felt as if my (real) hand were turning “rubbery.”
Q5	It appeared as if the seen rubber hand was drifting toward the right (towards my hand).
Q6	The seen rubber hand began to resemble my own (real) hand, in terms of shape, size, or some other visual feature.

2.7. Proprioceptive Drift toward the Rubber Hand

We measured the change in perceived finger position (proprioceptive drift, PD) as another criterion of RHI; however, it is known that the results do not always match with the subjective evaluation [20,48]. Immediately after each trial, the participants pointed the position of their middle fingers of their right hands using the index fingers of their left hands with their eyes closed. We instructed them to point 2–3 cm ahead of the fingertips of their middle fingers in a longitudinal direction to prevent them from touching the fake or actual right hands. The experimenter measured the distance between the actual and pointed positions of the middle finger in a parallel direction (Figure 3c). This measurement criterion was the same when the actual right hand was tilted 45° (Figure 3d). PD was defined as the

error in perceived finger position between the values before and after each trial. The drift toward the fake hand was denoted as a positive PD value.

2.8. Analysis

For each experimental condition, the subjective scores and PD values were averaged for the individuals. The normality of distribution of the responses to the questionnaire items and PD values were tested using the Shapiro–Wilk test. In the screening and main experiments, for each questionnaire item, the normality of the responses was rejected ($p < 0.05$) for more than one condition. Therefore, we compared the questionnaire responses among the conditions by the Wilcoxon signed-rank test (*exactRankTests* 0.8.31 for R) with the Bonferroni correction. In main experiment, we planned to apply two-way ANOVA on the two-by-two experimental conditions. However, upon obtaining the results of the Shapiro–Wilk tests, conditions 4 (sync. without a mirror), 5 (sync. with a mirror), and 7 (async. with a mirror) were compared to investigate the effect of the mirror and occurrence of the illusion. To calculate the PD values, the normality of their distribution was not rejected for any condition at the significance level of 0.05; hence, we compared them with *t*-tests and two-way ANOVA for the screening and main experiments, respectively.

3. Results

3.1. Results of Screening Experiment

Figure 4 shows the questionnaire responses and PD from the screening experiment.

3.1.1. Questionnaire Scores

The results of the questionnaire scores are summarized in Tables 3 and 4.

The scores of Q1 (body ownership) under the condition with a mirror were comparable to those without a mirror under synchronous conditions (Cond. 1 vs. Cond. 2, $p = 0.082$). The synchronization significantly increased the score of Q1 when gazing at the fake hand directly (Cond. 1 vs. Cond. 3, $p = 3.6 \times 10^{-4}$). Significant differences were also confirmed between the “mirror—synchronous” condition and the “direct view—asynchronous” condition (Cond. 2 vs. Cond. 3, $p = 3.6 \times 10^{-4}$).

In terms of Q2 (agency), the effect of the mirror was not significant under synchronous conditions (Cond. 1 vs. Cond. 2, $p = 0.77$). As with the result of Q1, the effect of synchronization was confirmed when directly gazing at the fake hand (Cond. 1 vs. Cond. 3, $p = 1.5 \times 10^{-3}$), and significant differences were confirmed between the “mirror—synchronous” condition and “direct view—asynchronous” condition (Cond. 2 vs. Cond. 3, $p = 2.1 \times 10^{-3}$).

These results indicate that illusory body ownership and agency were experienced when the mirror was adopted.

The scores of Q3–5 (i.e., control items) were negative under all conditions, whereas the scores of Q6 under the “mirror—synchronous” condition (Cond. 2) were greater than those under the “direct-view and asynchronous” condition (Cond. 3).

3.1.2. Proprioceptive Drift

The means and standard errors of PD were 1.15 ± 0.79 cm, 2.57 ± 0.66 cm, and 1.23 ± 0.89 cm for conditions 1, 2, and 3, respectively. Those for condition 2 (mirror-synchronous condition) were the largest; however, there was no statistically significant difference among the conditions (Cond. 1 vs. Cond. 2, $t(14) = 1.95$, $p = 0.21$; Cond. 1 vs. Cond. 3, $t(14) = 0.10$, $p = 0.99$; Cond. 2 vs. Cond. 3, $t(14) = 1.73$, $p = 0.32$). The values of PD exhibited small correlation coefficients with the scores of Q1 ($r = 0.21$, $t(43) = 1.43$, $p = 0.080$) and Q2 ($r = 0.26$, $t(43) = 1.75$, $p = 0.043$).

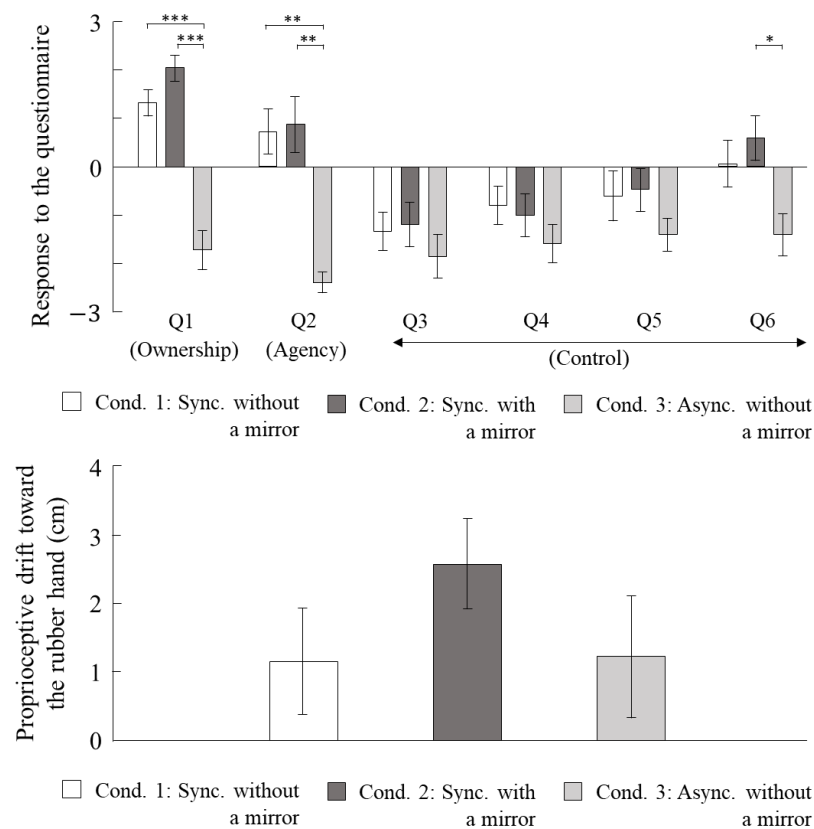


Figure 4. Participants' responses to the questionnaire and proprioceptive drift toward the rubber hand in the screening experiment. Means and standard errors among the participants. Asterisks *, **, and *** indicate $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively using the Bonferroni correction. Positive values of PD show that the position of the perceived hand was close to that of the fake hand. There was no statistically significant difference among the conditions for PD.

Table 3. Mean and standard error of subjective scores for Q1 (ownership) and Q2 (agency) in the screening experiment.

	Q1 (Ownership)	Q2 (Agency)
Condition 1 (congruent, direct-sync.)	1.33 ± 0.27	0.73 ± 0.46
Condition 2 (congruent, mirror-sync.)	2.07 ± 0.25	0.87 ± 0.58
Condition 3 (congruent, direct-async.)	-1.73 ± 0.41	-2.40 ± 0.21

Table 4. Summarized results of the screening experiment.

Q1 (Ownership)				
Cond. 1 (direct-sync.) vs. Cond. 2 (mirror-sync.)	$V = 3.5$	$t(28) = 2.11$	$p = 0.082$	Cliff's $\Delta = 0.39$
Cond. 1 (direct-sync.) vs. Cond. 3 (direct-async.)	$V = 105$	$t(28) = 8.09$	$p = 3.6 \times 10^{-4}$	Cliff's $\Delta = 0.84$
Cond. 2 (mirror-sync.) vs. Cond. 3 (direct-async.)	$V = 105$	$t(28) = 7.96$	$p = 3.6 \times 10^{-4}$	Cliff's $\Delta = 0.92$
Q2 (Agency)				
Cond. 1 (direct-sync.) vs. Cond. 2 (mirror-sync.)	$V = 15.5$	$t(28) = 0.62$	$p = 0.77$	Cliff's $\Delta = 0.13$
Cond. 1 (direct-sync.) vs. Cond. 3 (direct-async.)	$V = 90$	$t(28) = 7.69$	$p = 1.5 \times 10^{-3}$	Cliff's $\Delta = 0.82$
Cond. 2 (mirror-sync.) vs. Cond. 3 (direct-async.)	$V = 89.5$	$t(28) = 4.68$	$p = 2.1 \times 10^{-3}$	Cliff's $\Delta = 0.71$

3.2. Results of Main Experiment

Figure 5 shows the questionnaire responses and PD from the main experiment.

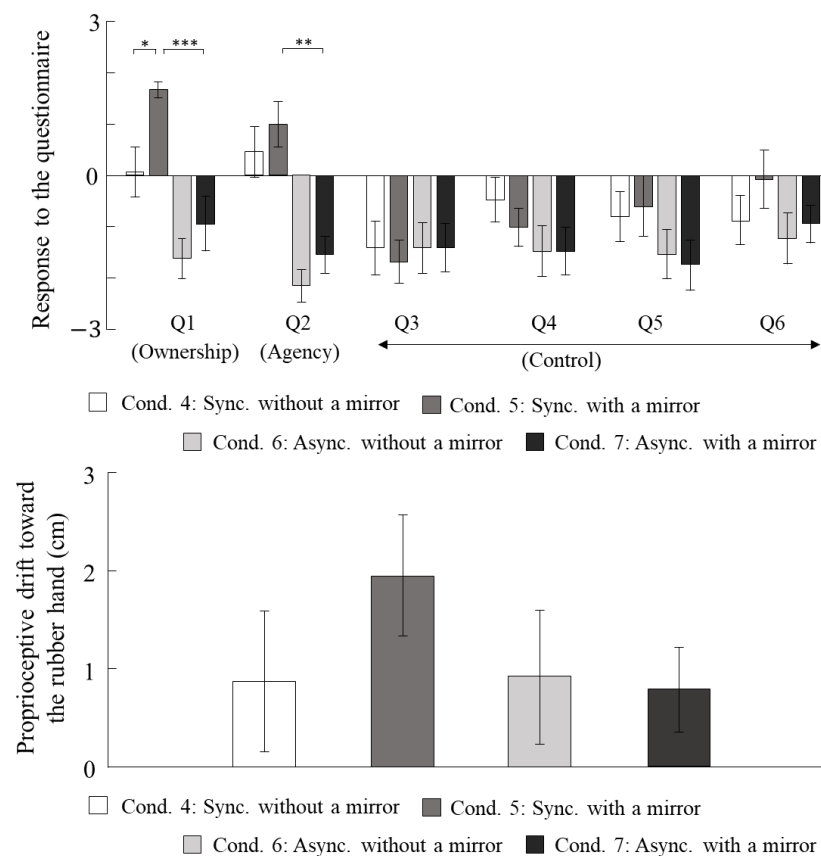


Figure 5. Participants' responses to the questionnaire and proprioceptive drift toward the rubber hand in the main experiment. Means and standard errors among the participants. Asterisks *, **, and *** indicate $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively using the Bonferroni correction. Positive values of PD show that the position of the perceived hand was close to that of the fake hand. PD was not significantly influenced by either the presence/absence of the mirror or the synchronization.

3.2.1. Questionnaire Scores

The results of the questionnaire scores are summarized in Tables 5 and 6.

The scores of Q1 (body ownership) were marginally greater when using a mirror (Cond. 4 vs. Cond. 5; $p = 0.023$) or when the hand motions were synchronized (Cond. 5 vs. Cond. 7; $p = 4.8 \times 10^{-4}$).

The scores of Q2 (agency) were significantly greater under synchronous conditions (Cond. 5 vs. Cond. 7; $p = 6.0 \times 10^{-4}$); however, the effect of the mirror was not detected at all (Cond. 4 vs. Cond. 5; $p = 0.70$).

For incongruent conditions, body ownership was more strongly induced when a mirror was adopted, and agency was induced regardless of the presence of the mirror. The scores of the control items were negative for all conditions.

3.2.2. Proprioceptive Drift

The means and standard errors of PD were 0.87 ± 0.71 cm, 1.95 ± 0.63 cm, 0.93 ± 0.69 cm, and 0.79 ± 0.43 cm for conditions 4–7, respectively. The effects of the mirror ($F(1, 59) = 0.56$, $p = 0.47$), the synchronization ($F(1, 59) = 0.79$, $p = 0.38$), and their interaction ($F(1, 59) = 0.94$, $p = 0.34$) were not significant. PD was not significantly influenced by either the presence/absence of the mirror or by the synchronization. Similar to the screening experiment, the values of PD exhibited small but significant correlation coefficients with the scores of Q1 ($r = 0.30$, $t(58) = 2.38$, $p = 0.010$) and Q2 ($r = 0.24$, $t(58) = 1.88$, $p = 0.032$).

Table 5. Mean and standard error of the subjective scores for Q1 (ownership) and Q2 (agency) in the main experiment.

	Q1 (Ownership)	Q2 (Agency)
Condition 4 (incongruent, direct-sync.)	0.07 ± 0.49	0.47 ± 0.50
Condition 5 (incongruent, mirror-sync.)	1.67 ± 0.16	1.00 ± 0.45
Condition 6 (incongruent, direct-async.)	−1.60 ± 0.40	−2.13 ± 0.32
Condition 7 (incongruent, mirror-async.)	−0.93 ± 0.53	−1.53 ± 0.36

Table 6. Summarized results of the main experiment.

Q1 (Ownership)				
Cond. 4 (direct-sync.) vs. Cond. 5 (mirror-sync.)	$V = 3$	$t(28) = 2.69$	$p = 0.023$	Cliff's $\Delta = 0.51$
Cond. 5 (mirror-sync.) vs. Cond. 7 (mirror-async.)	$V = 91$	$t(28) = 3.33$	$p = 2.4 \times 10^{-4}$	Cliff's $\Delta = 0.68$
Q2 (Agency)				
Cond. 4 (direct-sync.) vs. Cond. 5 (mirror-sync.)	$V = 15$	$t(28) = 0.86$	$p = 0.80$	Cliff's $\Delta = 0.2$
Cond. 5 (mirror-sync.) vs. Cond. 7 (mirror-async.)	$V = 76.5$	$t(28) = 3.52$	$p = 2.9 \times 10^{-3}$	Cliff's $\Delta = 0.72$

4. Discussion

We investigated the effect of the mirror images when there was spatial incongruency between the fake and veridical hands. Here, the results of the two experiments are briefly summarized and compared with previous studies, and reasons underlying the effect of the mirror are discussed.

In the screening experiment, illusory body ownership and agency were experienced by the participants in our experimental environment when they viewed the fake hand in a mirror. No significant differences were confirmed from the magnitude of PD, whereas conditions 2 (congruent hand posture, mirrored view, and synchronous) and 5 (incongruent hand posture, mirrored view, and synchronous) tended to exhibit greater PDs. With an increase in the number of participants or repetition of measurements, the statistical judgment may change for these two conditions. Although the experimental environments are different, these results are supported by Jenkinson and Preston [15], who investigated mirror-RHI involving active hand movements. Thus, the reproducibility of these experiments is promising. The significant difference in PD values between direct and mirror-viewed conditions were not confirmed, but the difference in the subjective ownership reports was observed between these conditions. As mentioned before, PD does not always match the subjective reports [48]. Other related studies have reported body ownership through a mirror to the same extent [13] or weaker [14] compared to the condition without a mirror, whereas these studies investigated passive RHI.

In the main experiment, ownership over the fake hand was observed even when the fake and actual hands were spatially incongruent in terms of the hand angle. In our experiment, the postural incongruency of the hand was observed to potentially disturb the ownership illusion, as suggested by the post hoc comparison of the ownership scores between conditions 1 (direct-view and congruent, score = 1.33 ± 0.27) and 4 (direct-view and incongruent, score = 0.07 ± 0.49) ($V = 47$, $t(28) = 2.02$, $p = 0.052$). Body ownership, which should have been weakened by postural incongruency, was strengthened using a mirror. The subjective ownership scores for conditions 2 (congruent, mirror-view, and synchronous, score = 2.07 ± 0.25) and 5 (incongruent, mirror-view, and synchronous, score = 1.67 ± 0.16) did not exhibit a significant difference ($V = 36$, $t(28) = 1.53$, $p = 0.14$), suggesting that the ownership illusion was induced without respect to the hand angles when the mirror was used (Note that these conditions across the screening and main experiments were not planned to be tested originally.). In contrast, the presence of a mirror did not affect agency in spatially congruent and incongruent conditions. Postural incongruency tends to weaken body ownership; however, it does not affect agency in active RHI [37,38,45,49]. This is known as the dissociation between ownership and agency. Nonetheless, they can interact with each other, which has been demonstrated in the RHI condition of a mirror [15]. The correlation coefficient between the subjective scores for agency and

ownership suggests their interaction. In the screening experiment, ownership and agency did not exhibit any meaningful correlation coefficients under conditions 1 (direct view, $r = 0.13$, $t(13) = 0.46$) and 2 (mirror view, $r = 0.09$, $t(13) = 0.34$). In these conditions, the veridical and the observed hands were aligned; herein, the sense of agency could have been easily evoked while being unaffected by ownership. In contrast, in the main experiment wherein the hand postures were incongruent, the two types of subjective scores were slightly (but not significantly) correlated under conditions 4 (direct view, $r = 0.38$, $t(13) = 1.48$, $p = 0.16$) and 5 (mirror view, $r = 0.47$, $t(13) = 1.91$, $p = 0.078$ with the Bonferroni correction). In these conditions, ownership might have positively affected the sense of agency. We could have discussed the effects of agency or voluntary motion on ownership further, had we investigated the passive RHI conditions under a spatially incongruent environment. Unfortunately, we did not conduct tests on passive conditions.

The mirror-induced enhancement of the illusion could be explained by three reasons.

First, there is the perceptual tolerance to incorrect mirror reflection. People largely pay little attention to the optical correctness of mirrored images [16,18,19]. They also update their internal body models upon seeing their body parts in a mirror [20,21]. The mirror reflection was not manipulated and optically correct in the present study; however, because of these intrinsic properties of mirrored images, the seen hand was more easily regarded as the participant's veridical hand despite the angle incongruency between the fake and veridical hands. In other words, the participants did not see the tilted fake hand in the mirror as unnatural. We think this explanation agrees with the implicit hypothesis in [13].

The second reason is that visual cues are weakened by a mirror, which accelerates multisensory integration. The body-ownership illusion is considered to be caused by the integration of visual, tactile, and proprioceptive cues in active RHI, and a greater degree of integration would produce a more intense illusion. Multisensory integration is enhanced when the stimuli to individual sensory channels are weak [22,23,50]. This is known as inverse effectiveness [24] and it is one of the three aspects of RHI: spatial rule, temporal rule, and inverse effectiveness. In our experiment, using a mirror might have weakened the light intensity of the visual stimuli, which could be related to the principle of inverse effectiveness, and multisensory integration might have been enhanced relative to the settings without a mirror.

Third, a mirror reduces the reliability and precision of visual cues and masks the inconsistency of perceived signals. For example, depth perception and judgment of mirrored images are inaccurate [51,52]. Provided that the perceived hand is determined by a multisensory integration process of sensory cues [53–56], less reliable or imprecise images in a mirror may alter the weightings of unisensory signals for multisensory integration [15] to maximize the resultant reliability after integration. For instance, in a visual–haptic integration task, a decrease in the reliability of visual cues led to a relative increase in the contribution of haptic cues [25–27]. Therefore, illusory body ownership would be influenced by the change in weightings of multisensory cues. In our experimental settings, visual, tactile, and proprioceptive cues were involved, and using a mirror degraded the reliability in terms of the visually provided hand posture. The weightings of sensory cues would be different between conditions with and without a mirror. Such an effect of less reliable images in a mirror was noted in [14], in which even laterality was masked using mirror images of a fake hand. In other words, in classical RHI settings where the fake hand is gazed at directly, because of the greater contribution of visual cues, visible incongruency may cause the visual sense to fail to capture other cues and prevent the occurrence of the illusion.

Some limitations of the present study lie in the experimental design. We note that the general disadvantages of the within-subjects design hold true for our study as well—i.e., problems associated with learning or after-effects. In our paradigm, a trial in which the illusion was elicited might have affected the subsequent trials [44]. Our hypothesis is that using the mirror influenced the incongruency between the visual and proprioceptive cues. However, in our experiments, tactile cues were also involved, and it is unclear that how visuotactile congruency/incongruency affected the

results. In the future, the experiment will be repeated with either active hand motion or tactile stimuli, whereas tapping or rubbing in the present study caused both motion and tactile stimuli simultaneously. Another limitation may be the weak control of active hand motions. We cannot deny that the results could have been influenced by the differences in the individual motions—i.e., tapping or rubbing and the frequency of their motions.

5. Conclusions

This study investigated the role of gazing at a fake hand in a mirror under RHI conditions with the hypothesis that the mirror image moderates the requirements of spatial congruency. The illusory experiences of body ownership and agency were evoked in our experimental environment when the spatially congruent fake hand in a mirror was gazed at (screening experiment), which agrees with earlier studies. The magnitudes of subjective experiences were equally high compared with the condition where the fake hand was directly seen without a mirror. Furthermore, using the mirror, the illusory experience was reported even when the actual and fake hands were placed at incongruent postures (main experiment). The mirror images might have weakened the relative importance of visual cues in the sensory integration process of RHI and eased the requirements of spatial congruency. Although the underlying mechanism of these observations remains to be studied, gazing at a fake hand in a mirror offers a promising approach for robustly inducing RHI experiences.

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