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Active Movements Generate Rotation-Independent Representations for Haptic Movements

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It has been reported that there are separate representations of visual and haptic movements, and that the haptic process has a rotation-independent representation for movements. This finding suggests that movement representations are formed in a different manner from object representations through visual and haptic signals because signals from visual and haptic modalities are processed in a common multimodal representation for object perception. Here, we investigated how the rotation-independent representation specific to haptic movements is generated. Our results show that rotation-independent representations of haptic movements do not appear when haptic movements passively occur. We also confirmed that active haptic movements generate rotation-independent representations. These results suggest that active movements are required to generate rotation-independent representations for haptic movements.

KEYWORDS: perception, vision and haptics, mental rotation, movement representation, psychophysics

1. Introduction

We move our hands to write and draw, typically while viewing the hand movements. In such situations, our perceptual system receives a simultaneous flow of information from vision and haptics. These different sources of sensory information form either one common representation or modality-dependent representations of movement in the perceptual system. A number of studies have investigated how signals from visual and haptic modalities are processed and have suggested the existence of a common visuo-haptic object representation (Pellizzer and Georgopoulos, 1993; Easton *et al.*, 1997; Ballesteros *et al.*, 1998; Zangaladze *et al.*, 1999; Amedi *et al.*, 2001; Ernst and Banks, 2002; Pietrini *et al.*, 2004; Merabet *et al.*, 2004; Woods and Newell, 2004; Lacey *et al.*, 2007; Giudice *et al.*, 2011; Matsumiya, 2013; Lacey and Sathian, 2014). These studies focused on object representations and there are only a few studies for representations of movements. There is a dichotomy between the action-related (dorsal) pathway and the perception- or object-recognition-related (ventral) pathway in visual processing (Livingstone and Hubel, 1988; Goodale and Milner, 1992; Merigan and Maunsell, 1993), so the representation of movement information likely differs in many ways from that of object information. Indeed, a recent study revealed separate and different representations of vision and haptics for movement processing (Shioiri *et al.*, 2013). That study showed that the mental rotation effect for haptic movements differs from that for visual movements. Studies of mental rotation show that people have the ability to mentally rotate a visual or haptic representation and the time required to do so increases with rotation angle (Shepard and Metzler, 1971; Cooper and Shepard, 1973; Sekiyama, 1987). However, Shioiri *et al.* (2013) revealed that the time required to mentally rotate a representation is independent of rotation angle for haptic movements but dependent on rotation angle for visual movements. This suggests that, for movements, the haptic process has a rotation-independent representation, which is different from the visual process. This could be a unique feature of the haptic process.

A critical issue is how the rotation-independent representation of haptic movement signals is generated and accessed. When we write a letter or draw a picture, we actively move our hand. Therefore, active movements might be an important factor in generating and accessing the rotation-independent representation for haptic movements. Since Shioiri *et al.* (2013) used active haptic movements in a test phase, here we examined whether passive haptic movements are sufficient to access the rotation-independent representation. A previous study has suggested that visual imagery is involved in haptic perception (Sathian *et al.*, 1997). Recent brain imaging studies have shown that haptic movements induce brain activity in the human middle temporal cortex (hMT+/V5) that is well known as a visual motion sensitive area (Matteau *et al.*, 2010; Wacker *et al.*, 2011). These studies suggest that haptic movement perception is generated by triggering visual imagery or by directly activating the visual cortex. In these studies, haptic stimuli were passively presented to participants. Therefore, we hypothesized that passive haptic movement signals generate a visual

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representation by triggering visual imagery or by directly activating the visual cortex. If this is true, we would expect to find that rotation-dependent visual representations are used in a test with passive haptic movements.

We conducted two experiments to test this hypothesis. The experiments used two-stroke patterns that were shown by visual or haptic movements as in Shioiri *et al.* (2013). In Experiment 1, strokes were always presented passively including haptic tests. In the learning phase, a movement pattern was presented either visually on a display or haptically via a force-feedback device. In the subsequent test phase, the movement pattern was rotated in an angle and presented passively. There were identical and mirror test patterns as in a typical mental rotation experiment (Shepard and Metzler, 1971; Cooper and Shepard, 1973; Sekiyama, 1987). The identical test pattern was a rotated version of the learned pattern and the mirror test pattern was a rotated version of the mirror image of the learned pattern. The participants were asked to recall the learned pattern and to judge whether the test pattern was the identical or mirrored image. The results of Experiment 1 showed that the passive haptic test did not induce a rotation-independent representation but a rotation-dependent representation, which suggests that a representation similar to a visual one was used to perform the task in the passive haptic test. This also implies that haptic information might generate a visual representation. We conducted Experiment 2 to confirm that active movements in a test phase are necessary to access a rotation-independent representation for haptic movements. In addition, we also examined in Experiment 2 whether there exists a special visual stimulus that uses a rotation-independent representation in learning a movement pattern. Following from the hypothesis that haptic information might generate a visual representation, visual information might also generate a haptic representation. To examine this question, we used the movements of a computer graphics (CG) hand as a visual stimulus and manipulated the orientation of the CG hand relative to the participant's hand. We considered two cases: congruent CG hand and incongruent CG hand. The congruent CG hand was aligned with the participant's hidden hand. The incongruent CG hand was rotated 180° relative to the participant's hidden hand. Since a CG hand moved on the display but the participant's hand was stationary in both cases, the congruent and incongruent CG hands moved irrelevantly to the participant's hand movements. Therefore, the incongruent CG hand would be seen as the hand movements of another person in front of the participant, but the congruent CG hand would be seen as an unowned visual object, not the participant's own hand. We expected that the incongruent CG hand might activate the process of imitating the action without actual hand movements. In addition, a previous psychophysical study has suggested that the imitation process forms motor representations of hand actions (Flanagan & Johansson, 2003). Other studies have shown that haptic information is important for the control of hand actions (Johansson & Flanagan, 2009) and that motor representations of hand actions are linked to haptic representations (Schettino *et al.*, 2015). Accordingly, a haptic representation might be involved in the imitation process. We examined whether the incongruent CG hand generates a haptic representation.

2. Experiment 1

2.1 Methods

2.1.1 Participants

Eight male students at Tohoku University participated in the experiments (age range, 22–24 years). All had normal or corrected-to-normal visual acuity. All participants were right-handed and they used their right hand for the experiment. The research was conducted in accordance with the principles expressed in the Declaration of Helsinki.

2.1.2 Apparatus

Visual stimuli were presented on a cathode ray tube display (Iiyama, HF703U, 46° width × 36° height, 75 Hz refresh rate), and the participant viewed the visual stimuli through a mirror. The participant grasped the stylus of a force-feedback device (Sensable, PHANTOM Omni) with the right hand below the mirror. The left hand was relaxed on the desk or a knee. A chin rest was used to immobilize the head and maintain a viewing distance of 38 cm. The force-feedback device produced a virtual haptic plane, which was spatially aligned with the image of the visual display surface reflected in the mirror. The position of the stylus of the force-feedback device coincided with the cursor on the visual display. The positions of the stylus were recorded at the same rate as the display's refresh rate of 75 Hz. This room did not have any light source other than the display.

2.1.3 Stimuli

The stimuli were a movement pattern of two strokes (Fig. 1). The lengths of each line segment in the movement pattern were 20 and 40 mm (3.0° and 6.0° in visual angle), and the angle between the two segments was varied randomly. The mirror pattern was defined as the pattern that was mirror-symmetric about the long line segment. The visual stimulus was a yellow disk with a diameter of 0.6°. The luminance of the disk was 125 cd/m^2, and the luminance of the background was 0.75 cd/m^2. The haptic stimulus was the movement of the stylus of the force-feedback device. A computer controlled the stylus movement, so the participant' hand was passively moved by grasping the stylus. The speed of the disk and stylus was 6.0 cm/s (9.0°/s).

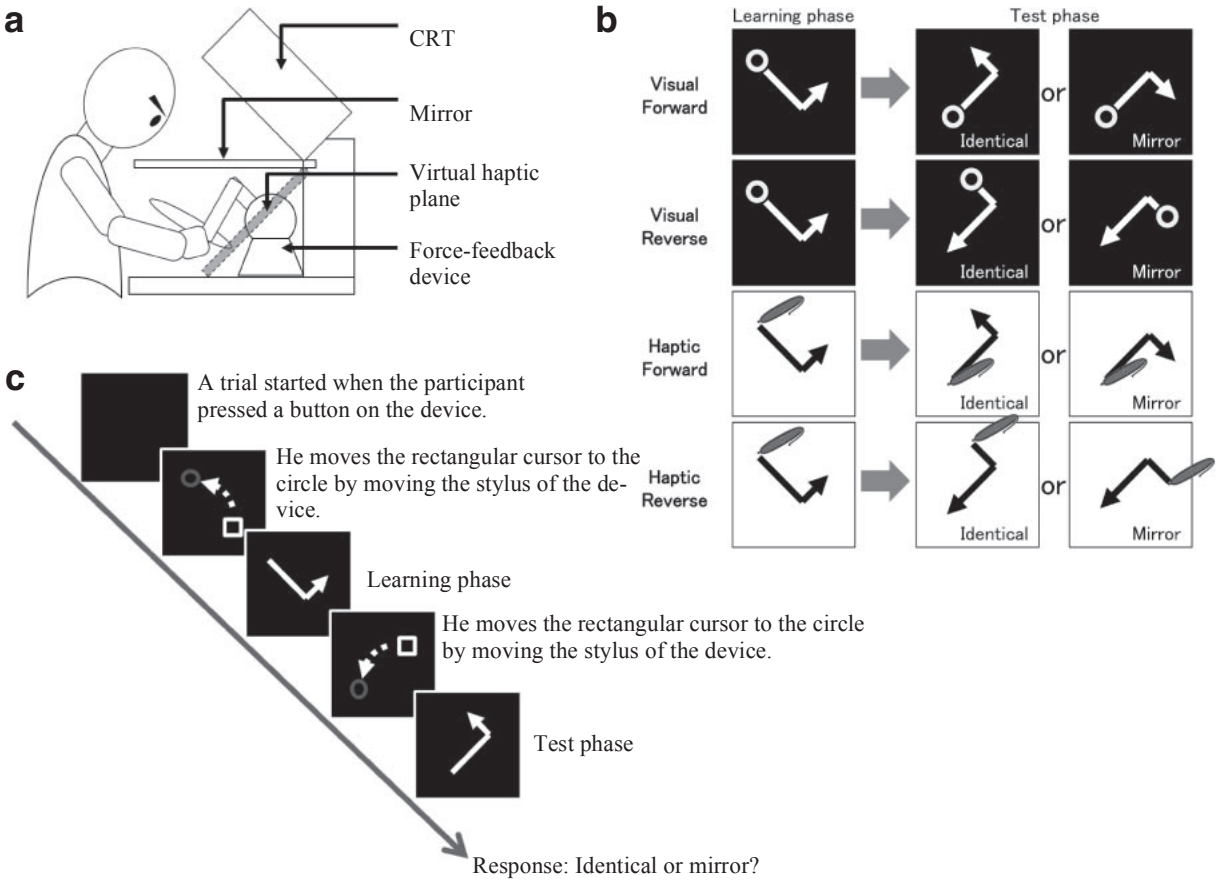


Fig. 1. Apparatus, stimuli, and procedure for Experiment 1. (a) Apparatus. Visual stimuli were presented on a cathode ray tube (CRT) display. The participant viewed them through a mirror while moving the stylus of a force-feedback device behind the mirror. A virtual haptic plane was spatially aligned with the virtual visual display. (b) Stimuli. The stimulus was a movement pattern of two strokes. Four conditions were Visual Forward, Visual Re-verse, Haptic Forward, and Haptic Reverse. In the Visual Forward and Visual Reverse conditions, a computer moved a yellow disk on the display. In the Haptic Forward and Haptic Reverse conditions, the computer moved the stylus of the force-feedback device that was held in the participant's right hand. The order of stroke in the test phase differed between the forward and reverse conditions for each sensory modality. (c) Procedure. Before each learning and test phase, the participant was instructed to move the rectangular cursor of the stylus to the red circle presented on the display. After the test phase, the participant pressed a button as soon as possible to report whether the two two-stroke patterns were identical or mirrored.

2.1.4 Procedure

Either visual or haptic stimulus was used in the learning and test phases. The stimulus was a two-stroke pattern presented either by a moving visual disk or by a haptic force from the stylus of the force-feedback device that the participant grasped (see Fig. 1a). Four conditions were defined as follows: (i) Visual Forward, the visual stimulus was used for both the learning and test phases and the order of a two-stroke pattern was the same for both phases (the visual stimulus moved the long distance and then it moved the short distance, or it moved in the opposite order); (ii) Visual Reverse, the visual stimulus was used for both the learning and test phases and the order of the two-stroke pattern differed between the two phases (the visual stimulus moved the long-to-short distance in the learning phase and then it moved the short-to-long distance in the test phase, or the visual stimulus moved in the opposite way between the learning and test phases); (iii) Haptic Forward, this condition was identical to the Visual Forward condition except that the stimulus was haptic; and (iv) Haptic Reverse, this conditions was identical to the Visual Reverse condition except that the stimulus was haptic (Fig. 1b).

The direction of the first stroke was randomly chosen in each trial with the restriction that the same percentage of trials was selected for four evenly divided angle ranges: -45° to 45°, 45° to 135°, 135° to 225°, and 225° to 315°. The angle between the two lines of the two-stroke pattern was randomly chosen between -90° and 90° relative to the line drawn by the first stroke. In the test phase, the two-stroke pattern was either identical to or mirrored the one presented in the learning phase, although the two-stroke pattern was rotated by an angle that was randomly chosen for four evenly divided angle ranges: -45° to 45°, 45° to 135°, 135° to 225°, and 225° to 315°. The participant's task was to report whether the pattern in the test phase was identical to or mirrored the pattern presented in the learning phase. To perform the task, the participant mentally rotated the learned stimulus.

A trial started when the participant pressed a button on the force-feedback device (see Fig. 1c). A red circle was then presented at a location chosen randomly on the display, and the participant moved the tip of the stylus of the force-feedback device to the red circle. Then, 1.5 s after the stylus reached the red circle, the computer presented a two-stroke movement pattern in the learning phase. After that, the red circle was again presented at the location chosen randomly to start the test phase. 1.5 s after the stylus reached the red circle, the computer presented a two-stroke movement pattern in the test phase. Then, the participant pressed one of two buttons using the left hand to report whether the test pattern was an identical or mirrored pattern. The participant was instructed to press a button as soon as possible. The cue for the decision was the angle of the second stroke, so the participant could respond after the presentation of the second stroke of the test phase. In the Visual Forward and Visual Reverse conditions, the computer presented the two-stroke pattern by movement of the yellow disk, and the participant was instructed not to move the stylus of the force-feedback device that was grasped. In the Haptic Forward and Haptic Reverse conditions, the computer presented the two-stroke pattern by the stylus's movement.

Each session consisted of 64 trials (2 orders of short and long line segments in the learning phase $\times$ 2 angles between the two lines of a two-stroke pattern in the learning phase $\times$ 2 orders of short and long line segments in the test phase $\times$ 2 angles between the two lines of a two-stroke pattern in the test phase $\times$ 4 rotations), and each participant performed two sessions in each of the four conditions with the order of sessions counterbalanced between participants.

2.1.5 Data analysis

We measured response time from the end of the test presentation, and calculated the median of correct responses for each condition of each participant and the error rate of the response by using the data obtained from both of the identical and mirrored stroke-test patterns. To calculate median response time, we classified the data into four ranges of rotation angles: -45° to 45°, 45° to 135°, 135° to 225°, and 225° to 315° with the central angles of 0°, 90°, 180°, and 270°, respectively.

2.1.6 Results and discussion

Figure 2a shows response time, expressed as the average of individual medians, as a function of rotation angle for a learned stimulus. Different curves represent different conditions. Response time increased with the angle difference between the learned and test patterns (270° is -90°) for the Visual Forward, Visual Reverse, and Haptic Forward conditions. This is consistent with a conventional mental rotation effect, where longer times are needed for larger rotations (Shepard and Metzler, 1971; Cooper and Shepard, 1973; Sekiyama, 1987). In contrast, response time tended to be constant for the Haptic Reverse condition. A repeated measures analysis of variance (ANOVA) showed significant main effects of rotation angle ($F(3, 21) = 6.57$, $p < 0.01$) and stroke order ($F(1, 7) = 7.21$, $p < 0.05$), but there was no significant main effect of test sensory modality ($F(1, 7) = 0.26$, $p = 0.63$ *n.s.*). No significant interactions were found for all combinations ($F(1, 7) = 0.72$, $p = 0.43$ *n.s.* between test sensory modality and stroke order; $F(3, 21) = 2.25$, $p = 0.11$ *n.s.* between test sensory modality and rotation angle; $F(3, 21) = 1.47$, $p = 0.25$ *n.s.*

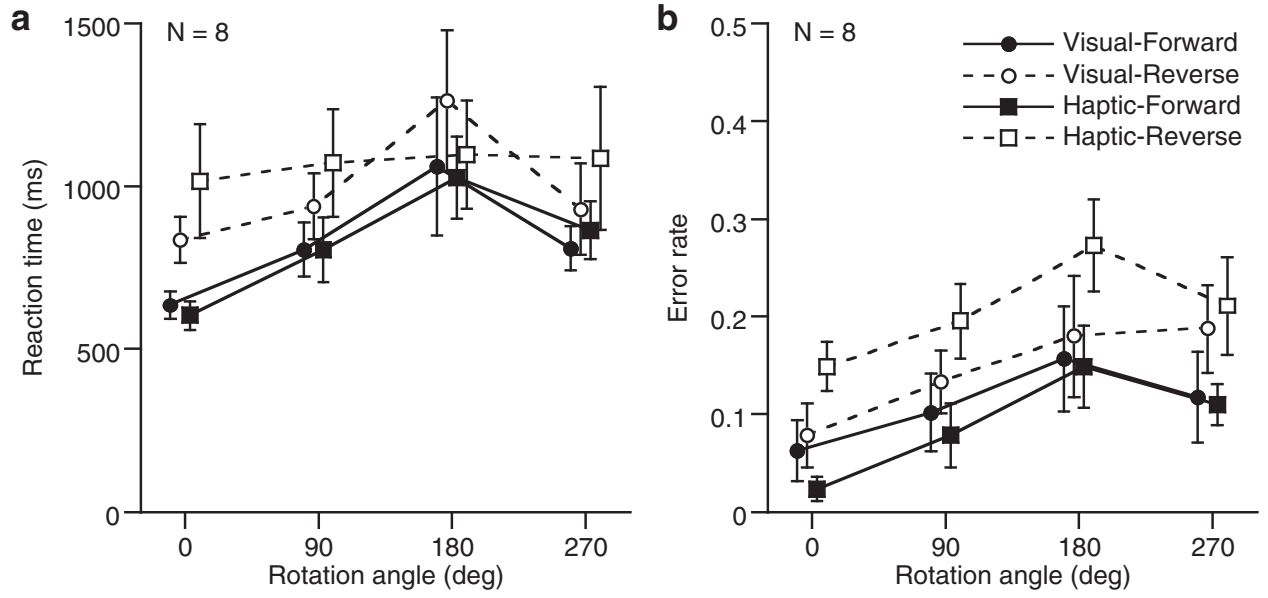


Fig. 2. Results for Experiment 1. (a) Average of median response times of eight participants as a function of rotation angle. (b) Average of error rates of eight participants as a function of rotation angle. Each symbol represents one of the four learning-test conditions. Error bars indicate standard error of the mean across participants.

between stroke order and rotation angle; $F(3, 21) = 2.23$, $p = 0.11$ *n.s.* among test sensory modality, stroke order, and rotation angle).

Figure 2b shows that the error rate increases with rotation angle for all the conditions. An ANOVA showed significant main effects of rotation angle ($F(3, 21) = 7.85$, $p < 0.01$) and stroke order ($F(1, 7) = 12.40$, $p < 0.01$) and interactions between test sensory modality and stroke order ($F(1, 7) = 11.56$, $p < 0.05$), but there was no significant main effect of test sensory modality ($F(1, 7) = 1.27$, $p = 0.30$ *n.s.*). No significant interactions were found for the combinations except the combination of test sensory modality and stroke order ($F(3, 21) = 0.25$, $p = 0.86$ *n.s.* between test sensory modality and rotation angle; $F(3, 21) = 0.05$, $p = 0.98$ *n.s.* between stroke order and rotation angle; $F(3, 21) = 0.79$, $p = 0.51$ *n.s.* among test sensory modality, stroke order, and rotation angle).

These results for both the reaction time and error rate indicate the similar effect of rotation angle between the visual and haptic modalities, which suggests that the rotation-independent representation for haptic movements found in Shioiri *et al.* (2013) was not used to identify movement patterns with passively haptic movements. Alternatively, one might see the effect of rotation angle on reaction time differ between the Visual Reverse and Haptic Reverse conditions, which leads to the interpretation that the result might be a consequence of the use of a rotation-independent representation for the Haptic Reverse condition with passive haptic movements. However, there were no significant interactions between test sensory modalities for the reaction time, and the error rate increased with rotation angle for the Haptic Reverse condition (Figure 2b) unlike Shioiri *et al.* (2013), who reported that the error rate was constant across all the rotation angles with active haptic movements. We could not draw the simple conclusion that the rotation-independent representation is used in the Haptic Reverse condition.

Experiment 1 indicated that passive movements of test patterns did not induce a rotation-independent representation but did induce a rotation-dependent representation for haptic movements, suggesting that passive movements generate a representation similar to a visual one.

3. Experiment 2

We conducted Experiment 2 to confirm that active movements in a test phase are necessary to use a rotation-independent representation for haptic movements. In addition, we also examined whether there exists a visual stimulus that generates a rotation-independent representation of haptic movements. Following the suggestion that haptic information might generate visual representations as in Experiment 1, visual information might also generate haptic representations. We used the movements of a CG hand as a visual stimulus, and manipulated the orientation of the CG hand. The CG hand which was rotated 180° relative to the participant's hidden hand (the incongruent CG hand) appeared to be the hand of another person. We hypothesized that the incongruent CG hand would generate a haptic representation because several studies have shown that imitation is based on a mechanism that matches the observed action of another person onto a motor representation of one's own action (Iacoboni *et al.*, 1999; Brass *et al.*, 2000).

3.1 Methods

We tested the same eight participants in Experiment 1. Stimuli in Experiment 2 were similar to those in Experiment 1. The visual stimulus was either a yellow disk or a realistic life-sized CG hand (Fig. 3a). The CG hand was presented at the same depth as the participant's hidden right hand, and was configured similarly to the participant's real hand. We varied the orientation of the CG hand (congruent or incongruent). In the congruent condition, the orientation of the CG hand was aligned with the participant's real hand. In the incongruent condition, the orientation of the CG hand was rotated 180° relative to the participant's real hand. We used four learning conditions, and in the learning phase a two-stroke stimulus was presented by one of four kinds of stimuli: (i) the yellow disk (visual learning); (ii) the haptic force (haptic learning); (iii) the congruent CG hand (visual learning); and (iv) the incongruent CG hand (visual learning).

The experimental procedure was also similar to that in Experiment 1, but the reproduction of a learned pattern was used in the test phase (Fig. 3b). The participant's task was to recall the learned stroke pattern and to show the second stroke in an appropriate rotation. In the test phase of all learning conditions, the computer presented the first stroke by the stylus's movement, and the participant was instructed to draw the second stroke by actively moving the stylus as soon as possible from the end point of the first stroke.

Each session consisted of 64 trials (4 rotations × 4 angles between the two lines of a two-stroke pattern × 4 first-line directions in the learning phase), and each participant performed one session in each of the four learning conditions with the order of conditions counterbalanced between participants.

We calculated the median of response latencies of stylus movement. Latency was defined as the time to start stylus movement from the end location of the first stroke. Correct response was defined as the case that the moving direction of the second stroke was within the range of ±45° around the correct direction. To calculate median latency, we classified the data of correct responses into four rotation angle ranges: −45° to 45°, 45° to 135°, 135° to 225°, and 225° to 315° with the central angles of 0°, 90°, 180°, and 270°, respectively.

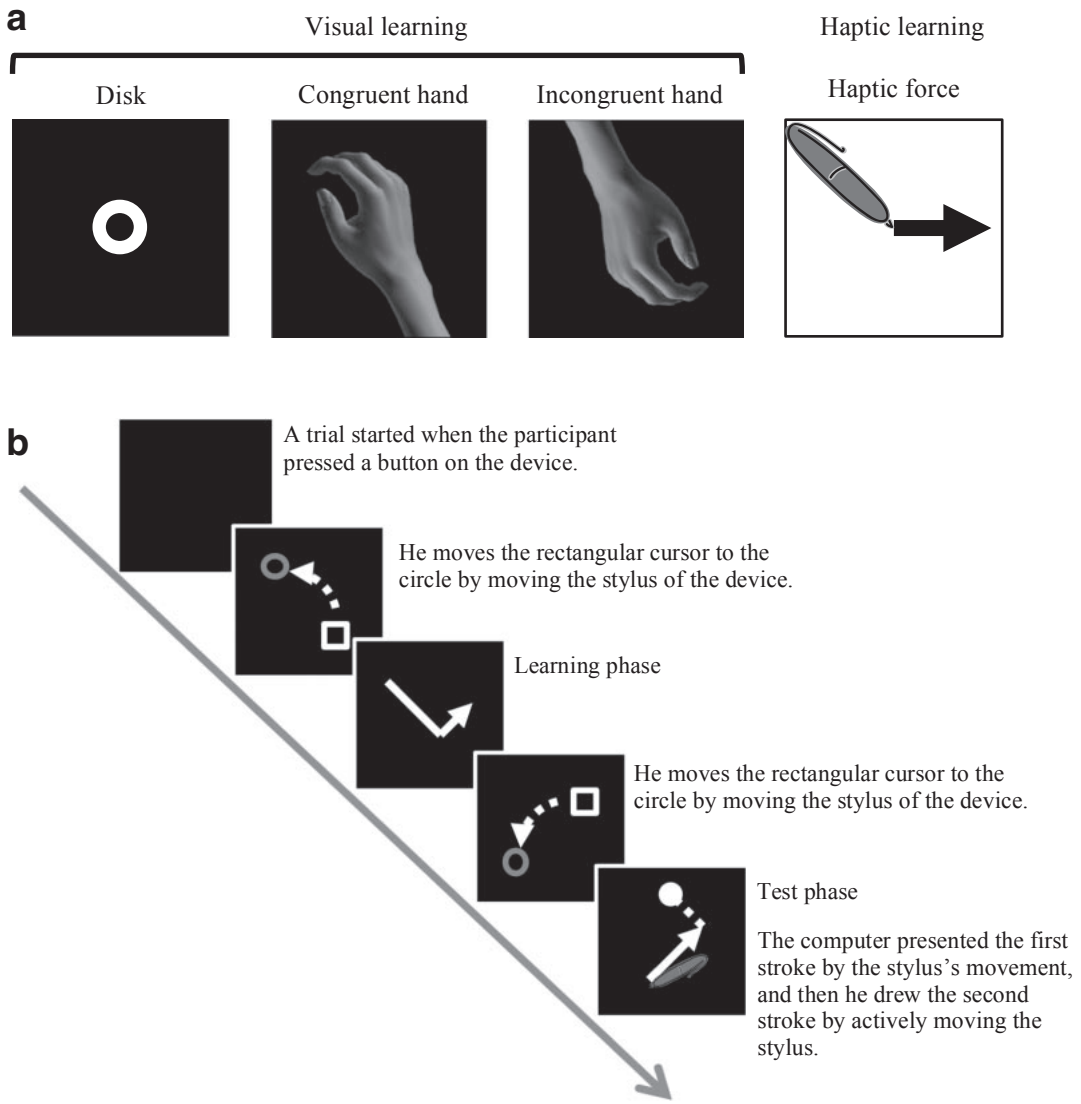


Fig. 3. Stimuli and procedure for Experiment 2. (a) Stimuli. The four learning conditions were disk, congruent hand, incongruent hand, and haptic force. The first three conditions were the visual learning condition and the last condition was the haptic learning condition. The hand images were generated by CG software. The hand image was life-sized. (b) Procedure. For all learning conditions, the test phase was the haptic test in which the computer moved a stylus to display the first stroke pulling the participant's hand, and then the participant drew the second stroke while continuously moving the stylus. Otherwise, the procedure was identical to that of Experiment 1.

3.2 Results and discussion

Figure 4a shows the average response latency as a function of rotation angle for a learned stimulus. Each curve represents a different condition. For the haptically learned stimulus, the average response latency was almost constant across rotation angles as in the previous study (Shioiri *et al.*, 2013), suggesting that active movements are required to access the rotation-independent representation of haptic movements. For the visually learned disk stimulus, it increased with rotation angle as with typical mental rotation experiments and visual movement conditions. For both types of CG hands, the average response latency increased with rotation angle. An ANOVA showed significant main effects of learning condition ($F(3,21) = 4.68$, $p < 0.05$) and rotation angle ($F(3,21) = 16.24$, $p < 0.001$), and interactions between learning condition and rotation angle ($F(9,63) = 2.86$, $p < 0.01$). The simple main effect of the learning condition was significant for the rotation angles of 90°, 180°, and 270° ($F(3,84) = 3.0$, $p < 0.05$, $F(3,84) = 9.32$, $p < 0.001$, and $F(3,84) = 2.89$, $p < 0.05$, respectively), but not for the rotation angle of 0° ($F(3,84) = 1.86$, $p = 0.14$ *n.s.*). On the other hand, the simple main effect of the rotation angle was significant for the learning conditions of the disk, congruent CG hand, and incongruent CG hand ($F(3,84) = 14.81$, $p < 0.001$, $F(3,84) = 12.93$, $p < 0.001$, and $F(3,84) = 4.25$, $p < 0.05$, respectively), but not for the learning condition of the haptic force ($F(3,84) = 0.42$, $p = 0.74$ *n.s.*). Table 1 shows the results of a paired *t*-test with correction for multiple comparisons (Ryan's method) for all the combinations for each of the rotation angles of 90°, 180°, and 270°. This test showed significant differences

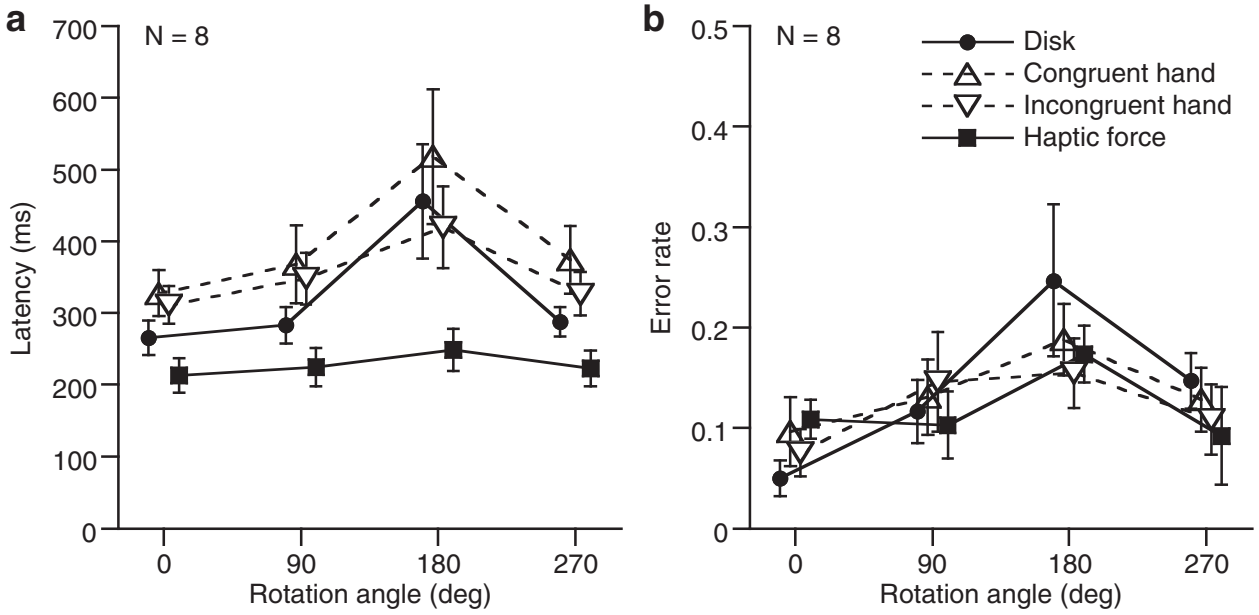


Fig. 4. Results for Experiment 2. (a) Average of median response latencies of eight participants as a function of rotation angle. (b) Average of error rates of eight participants as a function of rotation angle. Each symbol represents one of the four learning conditions. Error bars indicate standard error of the mean across participants.

Table 1. Results of a paired *t*-test with correction for multiple comparisons for response latencies in Experiment 2.

Pair	Rotation angle		
	90°	180°	270°
Cong CG hand vs Incong CG hand	$t_{84} = 0.37$ *n.s.*	$t_{84} = 1.85$ *n.s.*	$t_{84} = 0.89$ *n.s.*
Cong CG hand vs Haptic force	$t_{84} = 2.69$ *n.s.*	$t_{84} = 5.04$ $p < 0.05$	$t_{84} = 2.84$ $p < 0.05$
Incong CG hand vs Haptic force	$t_{84} = 2.32$ *n.s.*	$t_{84} = 3.20$ $p < 0.05$	$t_{84} = 1.95$ *n.s.*
Disk vs Cong CG hand	$t_{84} = 1.60$ *n.s.*	$t_{84} = 1.17$ *n.s.*	$t_{84} = 1.62$ *n.s.*
Disk vs Incong CG hand	$t_{84} = 1.23$ *n.s.*	$t_{84} = 0.68$ *n.s.*	$t_{84} = 0.73$ *n.s.*
Disk vs Haptic force	$t_{84} = 1.09$ *n.s.*	$t_{84} = 3.88$ $p < 0.05$	$t_{84} = 1.22$ *n.s.*

for four pairs (shaded in Table 1): between the congruent CG hand and the haptic force, between the incongruent CG hand and the haptic force, and between the disk and the haptic force at the rotation angle of 180°, and between the congruent CG hand and the haptic force at the rotation angle of 270°. These results indicate that the average response latency is similar across the learning conditions of the disk, congruent CG hand, and incongruent CG hand, and that the average response latency for the learning condition of the haptic force is different from that for the three other learning conditions.

Figure 4b shows the error rate as a function of rotation angle for a learned stimulus. The error rate increased with rotation angle for all the learning conditions. An ANOVA showed a significant main effect of rotation angle ($F(3, 21) = 5.96$, $p < 0.005$), but not for learning condition ($F(3, 21) = 0.30$, $p = 0.83$ *n.s.*). There were no significant interactions between learning condition and rotation angle ($F(9, 63) = 1.05$, $p = 0.41$ *n.s.*). The results of the error rate suggest that the error rate is similar across all the learning conditions, which is consistent with the results of Shioiri *et al.* (2013). They also reported the similarity among the learning conditions, although the error rate was constant across the rotation angles. These results confirmed that haptic movements are coded in the perceptual system as rotation-independent representations whereas visual movements are coded as rotation-dependent representations as in Shioiri *et al.* (2013). This suggests the existence of separate representations between visual and haptic movements.

These results confirm the existence of a rotation-independent representation for the haptically learned stimulus, and suggest that visual representations, rather than haptic representations, are dominant not only in the congruent CG hand

condition but also in the incongruent CG hand condition. We hypothesized that the rotation-independent haptic representation could be useful to match another person's hand movements onto the observer's own hand movements. If this is true, we expected to find that the effect of rotation angles was smaller with the incongruent CG hand than with the congruent CG hand, because the movements of the incongruent CG hand were likely identified as the movements of the other person's hand. However, the present results do not support the hypothesis. Why did the incongruent CG hand generate a visual, not haptic, representation in the present experiment? One possibility is that the incongruent CG hand did not appear like the real hand of another person. For that reason, the incongruent CG hand might generate a visual representation in the same way as the disk. Further investigations are needed to answer the question of whether the movements of the incongruent CG hand generate a haptic representation.

4. General discussion

A previous study suggested that for movements, the haptic process has a rotation-independent representation, which is different from the visual process (Shioiri *et al.*, 2013). In the present study, Experiment 1 showed that the test with passive haptic movements did not induce a rotation-independent representation. This result suggests that haptically learned rotation-independent representations were not always used in the test phase. Experiment 1 also showed that the haptic mental rotation effect in the passive haptic test was quite similar to the visual mental rotation effect in the visual test, suggesting that the test with passive haptic movements might induce a visual representation. Moreover, Experiment 2 confirmed that the test with active haptic movements induced a rotation-independent representation through the replication of Shioiri et al's (2013) experiment. In Experiment 2, the participant actively moved his own hand to recall and draw the learned movement pattern, whereas the participant's hand was passively moved in Experiment 1. Even for the same participants as in Experiment 1, a rotation-independent representation for haptic movements was observed in Experiment 2. Thus, these findings suggest that active movements are required for accessing a rotation-independent representation for haptic movements.

Our results show that rotation-independent representations for haptic movements are not accessed with passive haptic movements, whereas they are accessed with active haptic movements. These findings reveal that active movements induce rotation-independent representations for haptic movements. Signals arising from active movements activate motor representations of one's own action in the motor system (Jeannerod, 1997). In addition, active haptic movements provide a sense of voluntarily generating haptic stimulation by one's own action (Matsumiya and Shioiri, 2014). These two processes can contribute to recognition of one's own actions (Jeannerod, 2003). Therefore, we suggest that the rotation-independent representation for haptic movements might be linked to the mechanism for action recognition.

In addition, we explored whether representations for visual movements are close to the rotation-independent representations for haptic movements when the orientation of a CG hand presented in front of participants can be recognized as another's hand. Although the present study could not provide evidence to support that this hypothesis is true, here we discuss what mechanisms operate in the brain, assuming that the hypothesis is true. This is because it is important to consider the possible function of a rotation-independent representation for haptic movements. As mentioned above, the rotation-independent representation for haptic movements seems to activate a motor representation of one's own action. Therefore, we speculate that visually learning movements from another's body part might be based on the mechanism that maps the visual representation of the observed movements onto the motor representation of the same movements. This is consistent with the direct matching hypothesis for action understanding mechanisms mediated by the mirror neuron system (Gallese *et al.*, 1996; Rizzolatti *et al.*, 1996; Iacoboni *et al.*, 1999; Rizzolatti *et al.*, 2001). It would be useful to indicate whether the method developed in the present study provides a new tool for examining the mechanisms underlying the processing of action understanding in future investigations.

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