Effect of visuomotor learning in arm reaching movement on the visual boundary associated with the direction of target motion

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***Abstract*— This paper examines whether motor learning affects sensory function, in particular, visual perception in the context of a visuomotor learning paradigm involving arm reaching movements. An experimental task of arm reaching movements requires somatosensory and visual information to improve their performance in trials. The somatosensory perception, limb positional perception, has been reported to change during the motor learning. Then, we wonder whether the visual perception does not change even though it is utilized as the same as somatosensory perception during the reaching movement. To answer this question, we designed an experimental procedure that included visual tests before and after visuomotor learning. Among many characteristics of the visual perception, the perception of movement direction of a visual target, a cursor, was focused. In the normal motor learning task, participants repeat reaching movements to visual targets without seeing the actual movement of the arm: Instead, the cursor is presented to denote the current hand position. However, in our experiments, cursor was intentionally displayed in some deviations, more to the left or the right of the actual hand position. In the visual tests, the participants observed a cursor moving outward along the body midline, but deviating slightly to the left or the right. They were asked to indicate which side (left or right) the cursor was deviated to. From the participants' responses, we determined the visual perceptual direction that separated the left and the right, which we call here the visual boundary. The experiments with eight participants revealed that the visual boundary shifted in a direction opposite to that of the cursor display deviation, implying that the motor learning might affect visual perception.**

I. INTRODUCTION

Human movements are produced using information from the sensory feedback. For example, in arm reaching movements, the hand position, perceived through visual or somatosensation, becomes an important factor in determining which direction the hand should be moved next. This indicates that human movement generation is affected by our perceptions of position and motion. This will be true in robot systems as well, where positional data obtained from joint angle sensors such as rotary encoders influences the motion.

Then, is the reverse possible? That is, can movement or more specifically motor learning affect perception? Indeed, it has been recently reported that the motor learning affects somatosensory perception which in turn affects human reaching movements [1]. This phenomenon is equivalent to that, in the robot system, the robot's repetitive motions change the characteristics of positional sensors such as rotary encoders. Although this kind of sensory adaptation or recalibration has not been incorporated into recent robot systems, its introduction to the mechanical control system might change robot behaviors to resemble those of humans. From this point of view, this paper explores human sensory adaptation associated with motor learning.

Human reaching movements usually utilize not only somatosensory but also visual information. This raises the possibility that visual perception might change with the motor learning. Vahdat et al. [2] using fMRI analyses found that not only the motor cortex, but also somatosensory cortex can change in association with motor learning. In monkey cortices, there are connections between motor cortex and visual areas [3] as well as between motor cortex and somatosensory cortex [4]. These findings suggest that visual perception might be affected by motor learning as has been previously shown for somatosensory areas. In effect, the presence of anatomical connections provide us with the possibility that visual perceptual changes accompany motor learning.

In this study, our aim is to test for the possibility of a change in visual perception associated with motor learning in the reaching movements. We have used a variant of a visuomotor adaptation task. In previous work on visuomotor adaptation, proprioceptive changes [5], and distortions of shape perception [6] have been reported. Most studies have focused on the somatosensory perception of hand position, whereas possible effects of learning on visual perception have received less attention. Barduc and Wolpert [7] demonstrated that visual remapping depends on the arm trajectory in joint space. Brown et al. [8] examined the effect of force-field learning on visual motion prediction and found that learning systematically alters perception of movement speed. In the present paper, rather focusing on than the speed of a visual target, we evaluate the perception of motion direction. Prism adaptation [9], which has been shown to

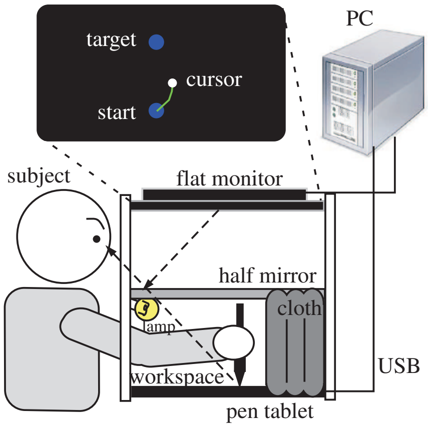


Fig. 1. Experimental setup.

aid in rehabilitation for visual neglect patients [10], is a frequently used technique to study motor learning in healthy adults [11], [12]. In the present study, in comparison with prism adaptation, which perturbs the whole visual field, we apply a positional perturbation of a visual target in which only the visual target position is displaced.

II. Idea and Expectation

A. Introduction of visuomotor learning

We have previously proposed a model of human motor learning that accounted for changes in somatosensory perception [13]. This model described somatosensory adaptation that was triggered by the adjustment of the desired trajectory of the hand. In that work, the desired trajectory following learning and the perceptual boundary shifted in the same direction. If visual perception also changes with motor learning and is related to the previously observed changes with somatosensory function, the adjustment of the desired trajectory may well be a crucial factor in determining the direction of the visual perceptual shift.

Adjustments of the hand trajectory have been studied extensively in visuomotor adaptation tasks, in which the visual target is gradually displaced relative to the actual hand position during movement repetitions in motor learning. It has been reported that somatosensory adaptation takes place in conjunction with changes in hand movement direction even in visuomotor learning [5]. Accordingly, we here have adopted visuomotor learning as an experimental model to investigate possible visual perceptual changes.

Figure 1 illustrates the experimental setup. Participants perform reaching movements while holding a pen. The pen is a part of pen-tablet system that detects the pen tip position (detectable area: 487.7mm $\times$ 304.8mm: spatial resolution: $\pm$0.25mm, time resolution: 200 Hz max.). By using this system, we record participants' hand movements. A flat computer monitor (size: 508mm $\times$ 286mm, resolution: 1920 $\times$ 1080 pixels) is installed over the workspace, and a semi-silvered mirror (half mirror) is placed in the middle, between the monitor and the tablet. A visual target and the cursor position are both displayed on the flat monitor and projected onto the half mirror: if the positional relationship between the flat monitor and the pen tip on the tablet is correctly calibrated, the cursor shows up exactly at the pen tip position, when the participant looks down on the workspace from a fixed position over the half mirror, as shown in Fig. 1. Using this projection system, we can indicate the start and target positions of the reaching movement.

If the workspace is illuminated by turning on a lamp, the participants can directly see the hand as well as the pen and its tip. On the other hand, darkening the workspace prevents participants from seeing the hand and pen. In the latter case, the visual information of the pen tip position comes only from the cursor projected on the half mirror.

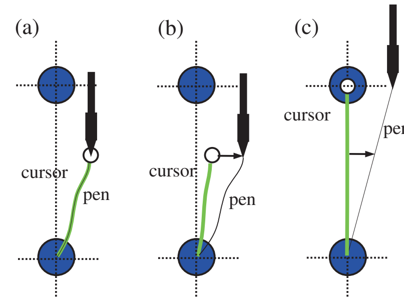


Fig. 2. Visuomotor learning in motor learning phase.

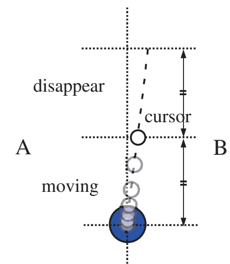


Fig. 3. Cursor movement in visual test.

B. Experiment design in preliminary test

A visuomotor adaptation task was used to study motor learning. Visual perceptual tests were performed before and after the learning.

The experimental setup described in section II-A allowed us to project the cursor position onto the half mirror, together with the start and target position of the reaching movement. In the motor learning task, the cursor could be displayed exactly at the position of the pen tip, as shown in Fig. 2(a), but we could also display it as intentionally deviated from the actual pen tip position. Here, from one movement to the next we gradually rotated the cursor position to the side, that is, to the right or the left, as depicted in Fig. 2(b). The amount of the lateral deviation over the course of any trial depended on how far the hand was from the start position. The instruction to the participants was to move the pen tip grasped by their hand so that the 'cursor' traveled directly from the start to the target. In order to satisfy this instruction, participants had to move the hand in 'diagonal' direction, as

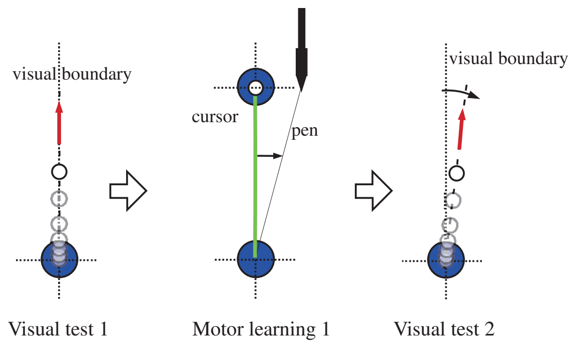


Fig. 4. Expectation of experiment.

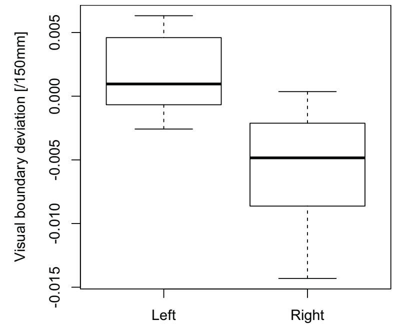


Fig. 5. Box plot of visual boundary changes for each cursor rotation direction in the motor learning task.

shown in Fig. 2(c), even though the target appeared straight ahead.

In the visual perceptual test, we showed the same size cursor that moved from the same start position as in the reaching movements, depicted in Fig. 3. This cursor traveled straight, but went leftward or rightward from the midline the body: The cursor movement was always diagonal. Participants were asked to answer which side the cursor movement was deviated to, to the left (A) or to the right (B). The visual test was repeated multiple times at each of deviation angle. From the participants' responses, the visual perception of the center direction that discriminates the left and the right, which we call here 'visual boundary', could be estimated using a psychometric function.

C. Expectation

Our expectation is illustrated in Fig. 4. Participants will learn the hand path that is needed to move the cursor straight from the start to the target position. This new hand trajectory that generates the deviated hand position results in a shift in visual perception. Specifically, the estimated center or body midline direction in the visual test (Fig. 4 (a) and (c)) will be different before and after the visuomotor learning (Fig. 4 (b)): the visual boundary would be shifted to the same side as the hand path that is learned in the visuomotor task.

III. Experiment

A. Preliminary test

In a preliminary experiment [14], arm reaching movements were performed in a center-out direction. Namely, the arm movement direction required to produce straight out movement was rotated gradually during visuomotor adaptation following the scenario in the previous section.

Before and after the reaching movements, the visual tests described in section II-B were conducted for each participant to detect the visual boundary between left and right. The deviations of the visual boundary relative to tests conducted before learning are presented in Fig. 5 for cursor rotation to the "Right" and "Left" in the motor learning: "Right" denotes that the hand deviates to the right because the cursor was displayed to the left with respect to the actual pen-tip position. The vertical axis represents the amount of the visual boundary deviation: the positive value indicate that the deviation occurred to the left direction.

This boxplot suggests that the visual boundary has changed in different directions which depend on the cursor rotation direction during motor learning, and in particular, opposite to the direction of cursor rotation. Statistically, a T-test revealed a significant difference in the visually estimated direction of body midline following learning(t = -3.9966,$p = 0.0008463 < 0.001$). Tukey's test, however, did not provide the significant difference among four groups, R1 (Right + Visual test1), R2 (Right + Visual test2), L1 (LEFT + Visual test1) and L2 (Left + Visual test2).

B. Improvement in experimental design

We expected that a clearer difference would be detected between the leftward and rightward cursor rotations in the preliminary experiment, but we did not find it. One possible cause may be the provision of the visual information regarding the visual test direction during the visuomotor training. Specifically, the cursor was displayed in a position that was different from that of the actual pen-tip. That is, in order for the cursor to move along the body midline, the hand trajectory had to deviate the side, but the cursor still moved straight along the body midline, because this was the goal that was set for the participants. Thus, in the visual test that followed learning, the center or midline direction might be unaltered visually, because the participants observed the true midline direction many times during the visuomotor learning.

To remove this effect, we modified the experimental adaptation procedure so as not to display cursor motion along the midline direction. The procedure was drawn from the literature on motor learning generalization. In general, the effects of the motor learning is not restricted to the area in which participants have conducted the learning task, but rather extend beyond this area. Such effects are called generalization of learning, and have been reported for both visuomotor learning [15] as well as force-field learning [16] in arm reaching movement.

A new experimental design is illustrated in Fig. 6. In the motor learning trials, the target is presented, not in the center area, but in the left or the right area of the workspace. The cursor position is laterally-deviated with respect to the actual

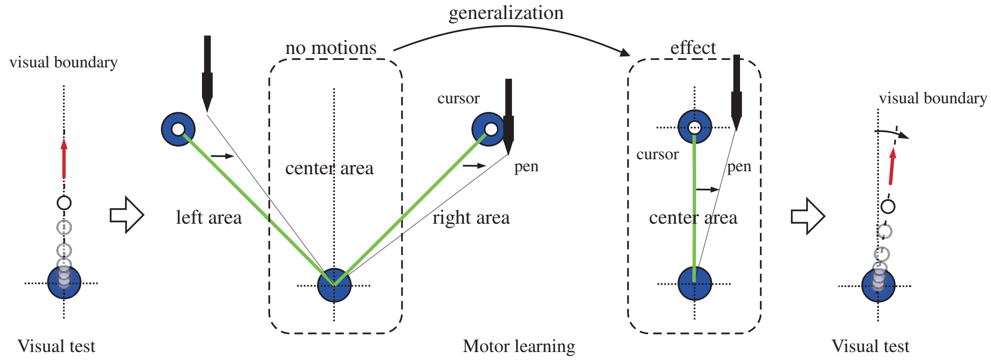


Fig. 6. Testing for visual perceptual change following motor learning utilizing generalization.

pen-tip, but its deviated direction is the same at both the left and the right. Fig. 6 shows the condition "Right" where the cursor is displayed to the left and thus hand position comes to move to the "Right". After the motor learning, the effect of learning are tested in the center area. It is our expectation that the visual boundary will shift to the right even in the center area, reflecting an effect of perception of hand position on visual perception.

C. Procedure

Figure 7 shows the experimental procedure. In baseline movements in *motor learning 1*, the cursor is displayed at the exact pen tip position, whereas its display position is rotated to either side depending on the condition "Left" or "Right" in *motor learning 2*. Three results using the identical visual test before and after visuomotor rotation learning are compared. *Visual test 1* and *visual test 2* are expected to be the same. On the other hand, in *visual test 3*, the visual boundary is expected to shift to the same direction of the motor learning condition comparing with *visual test 2*.

In the experimental setup, Linux (Ubuntu 18.04) was run on a personal computer as a controller, which detects the pen tip position every 10ms. Tcl/tk was utilized for graphic user interfaces, including the animation of cursor movements which was updated every 25ms.

Eight right-handed participants between 20-28 years of age were recruited for this test. Four participants each were assigned to two different motor learning conditions, "Left" or "Right".

This study was approved by the ethics committee on medical research in Gifu University Graduate School of Medicine (No. 29-115).

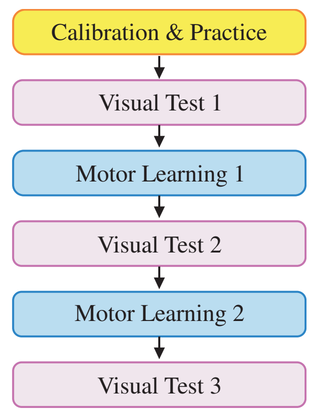


Fig. 7. Procedure of experiment.

D. Method

1) Motor learning: Participants were asked to sit on a chair in front of the experimental setup with their chin on a chin-rest to eliminate motion of the head. During the motor learning task, attention was given to the participant's posture to ensure that they remained in the center of the work space.

Participants were instructed to hold the pen of the pen tablet system with their right hand and perform reaching movements with the pen tip touching the tablet. The work place of the hand under the half mirror was darkened to prevent the participants from directly seeing the pen tip or their hand and arm.

The start position was 7.5cm inward from point that participants indicated as their own center position at the beginning of the experiment. Two target positions were set 15cm away from the start position, ± 45 degrees from the center direction.

At first, the cursor, a white circle of 0.75cm diameter, as well as the start position were displayed on the monitor. The participant was required to use the pen to move the cursor into the start position. When the cursor remained in the blue circle of the start position for 0.75s, the target position was presented. At the same time, a tone was sounded from the speakers connected to the PC. This provided a start signal for the reaching movement. The participants were to move the cursor to the target by using the pen on the tablet. During the reaching movement, the path of the cursor was shown as a green line to help participants improve their hand trajectory over the course of training.

The subject was required to maintain the cursor at the target position for 0.75s. Then, the target as well as the cursor trajectory disappeared to indicate the end of the trial. Afterwards, the participants had to move the hand back to the start position. During this time, the color of the start position turned red, green or remained blue. The color indicated the duration of the preceding reaching movement: red means too short, less than 0.9s, green means too long, more than 1.1s, and blue means good. Depending on the color, participants were required to adjust the speed of their next reaching movement.

In *motor learning 1* trials, the cursor was shown in the exact position of the pen tip. However, in *motor learning 2*, the cursor position is gradually rotated, over the course of the first ten trials, to the right in the condition "Left", such that the pen tip must be moved to the "Left" to compensate. In the condition "Right" the cursor was rotated leftward and thus the participant must move the pen tip to the right. Following the first ten trials, the magnitude of rotation held constant from the 11th to the 150th trial. Since the visual feedback was rotated, the amount of the cursor shift was proportional to the distance in the forward direction. This means that, at the start position, the cursor and pen tip positions are the same, but the distance between them reaches about 12mm around the target position, 15cm outward from the start position.

Both visuomotor rotation directions involved 150 trials. The target position at the left and right parts of the workspace was constant except for three catch-up trials at 50th, 90th and 130th trial. At this catch-up trial, the target appeared at the center position and the cursor was shown at the hand position without any visual perturbations.

2) Visual perceptual test: In the visual tests that preceded and following movement training trials, the participants were asked to observe cursor movements that are projected onto the half mirror. This cursor movement was designed to have the same start and target positions as the reaching movements in the motor learning phase, and was presented using a minimum jerk trajectory: the distance was 15cm and the duration was 0.825s. Note that whereas training movements were made at the left and the right of the workspace, the perceptual tests were conducted in the center.

Initially, the cursor and the start position were presented together. 1.25s later, the cursor moved from the start to the target position. The target position was situated 15cm from the start but it was not presented to the participants since it may have provided a directional cue defining the visual boundary. The cursor, on the other hand, traveled straight toward the invisible target with a slight lateral deviation. Moreover, the cursor movement was displayed only during the first half of the path, as depicted in Fig. 3, again to withhold information that could be used to infer the visual boundary. Therefore, participants were not able to see the cursor arrive at the target position. Only the movement direction of the cursor leaving the start position was available to participants.

0.825s after the cursor started moving, a random-dot pattern was displayed on the monitor to prevent judgments being made based on visual after-effects. During this period, the participants were required to answer question 'Which side did this cursor movement deviate towards, A (left) side or B (right) side?'

The purpose of this test is to detect the visual boundary, the midline direction that the participants regarded as straight out from the body. This was determined by perceptual testing using many cursor movements with the same or different deviations. The selection of the cursor deviation on any particular trial is carried out according to the PEST algorithm [17]. The initial values of PEST are selected at random order from the following six values: ± 0.04, ± 0.05, ± 0.06: these values mean a ratio with respect to the traveled distance 15cm (i.e., the value 0.04 corresponds to 15cm x 0.04 = 6mm left). The initial step size was 0.04 at the start of the PEST runs, and the minimum step size is 0.005. Participants completed 6 PEST runs in each experimental condition.

IV. Results

In each visual test, the responses "A (left)" or "B (right)" were obtained for each deviation. When the cursor deviations were large. e.g. to the left, the proportion of A responses approached 1.0, and to the right, the proportion of A responses became 0. However, for the small deviations, participants tended to sometimes say "A" and sometimes say "B" even for the same deviation: the proportion of A responses tended to increase with the magnitude of the deviations in the leftward direction. Here, the left direction is shown with positive values. Therefore, we approximated the relation between the A-response ratio and the cursor display deviation using the logistic function, a monotonically increasing function, and created a psychometric function.

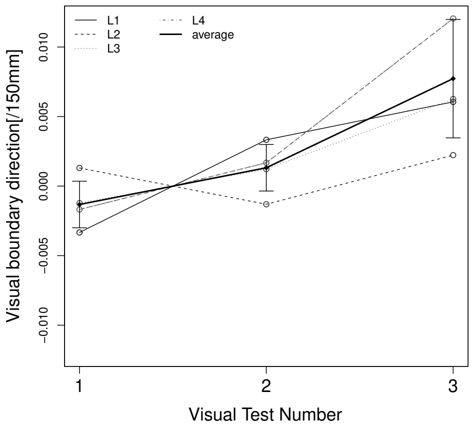
It would be natural to suppose that, when participants feel that cursor motion was straight forward, the ratios of the response "A" and "B" become the same. Therefore, the deviation at which the psychometric function representing the ratio of the response "A" takes 0.5 was regarded as the visual boundary between left and right.

Three visual tests were conducted for each subject and thus the three estimates of the visual boundary were obtained. These values were depicted for each subject separately: the "Left" group is shown in Fig. 8(a), while the "Right" group is shown in Fig. 8(b). The values on the vertical axis, for the visual boundary, denote the deviation to the left directional, and their magnitude has been normalized by the distance of the reaching movement, as mentioned in section III-D.2. For example, 0.01 corresponds to 1.5mm (15cm $\times$ 0.01) to the left, which is the deviation at the moment the cursor disappears in the midpoint of the path. Note that these graphs were realigned so that the average of the visual boundary in visual tests 1 and 2 is zero.

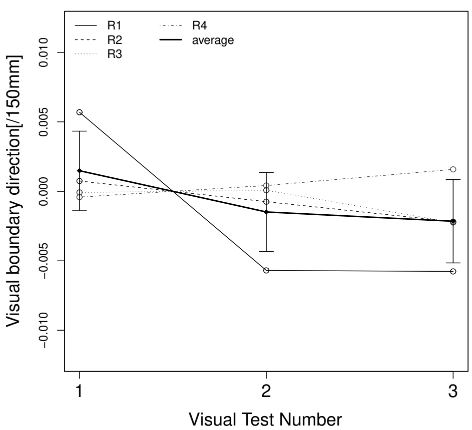
As can be seen, before and after the motor learning 2, the visual boundary increased for the "Left" condition whereas it decreased for the "Right" condition. ANOVA indicated the significant difference ($p = 0.0119 < 0.05$) among the average of the six groups (left or right $\times$ three visual tests). In addition, the Tukey's test detected that the difference between the "Left" and the "Right" condition for visual test 3 was significant ($p = 0.00433 < 0.01$).

V. Concluding remarks

Hypothesizing that motor learning affects the visual perception of motion direction, we designed an experimental



(a) Left condition



(b) Right condition

Fig. 8. Psychometric function.

procedure that involved an arm reaching task with altered visual feedback combined with visual tests before and after motor learning. In visual perceptual tests, we determined the visual boundary that the participants regarded as the center between the left and right. It was demonstrated that, if the visuomotor adaptation entails movements of the hand to the right (or left) side of the cursor, the visual boundary tends to make the same directional shift to the right (or left) in the following visual test. Using ANOVA, we found a significant difference in the group average for the visual boundary following adaptation. In particular, there was a reliable statistical interaction in terms of the visual boundary shift associated with cursor deviation direction during the motor learning and the effect of the motor learning on perception. More experiments should be conducted because N is still small.

Owing to an improvement in movement outside the training area based on the generalization of motor learning, the visual boundary shifted in a direction opposite to the cursor deviation (but in the direction of movement) before and after learning in seven of eight participants. We have not yet verified whether movement generalization occurred in our visuomotor learning experiment: the effect this paper confirmed was only changes in perception. In future work, we will need to measure the generalization effect, in a quantitative manner, and evaluate the relation between the magnitude of the visuomotor learning and the associated change in the visual boundary. And we would like to elucidate a human motor control mechanism with connecting the somatosensory as well as visual adaptation.

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