

Implicit transfer of mirrored spatial structure in visuomotor sequence learning

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Abstract

Implicit transfer in sequential learning can occur with some spatio-temporal structures but not with others. Here, we investigated whether the consistent mirror-reversal of visuomotor sequences would lead to implicit transfer. A "set" comprised three sequential button presses and seven consecutive sets comprised a "hyperset." Participants learned hypersets by trial and error with their right hand. Then, they learned another hyperset, in which each set was vertically mirrored, horizontally mirrored, or randomly generated. Even when the participants did not notice the mirrored rule, the mirrored hypersets led to implicit transfer in terms of accuracy for both vertical and horizontal reversals. Furthermore, the vertical reversal also led to implicit transfer of performance speed. Taken together, the present results suggest that people can implicitly apply their learned representations to the mirrored visuomotor sequences.

Keywords: Implicit learning; Sequential learning; Transfer; Mirror symmetry; Speed, Accuracy

Introduction

Implicit learning of behavioral sequences play an important role in our daily life. Our cognitive abilities such as language usage, playing the piano, and driving a car can be improved by implicit acquisition or learning of skills (see reviews for implicit learning; Abrahamse, Jiménez, Verwey, & Clegg, 2010; Perruchet & Pacton, 2006). In fields of cognitive science, cognitive psychology, or experimental psychology, several implicit learning paradigms have been proposed (e.g., Serial Reaction Time (SRT) task, Nissen & Bullemer, 1987; artificial grammar learning (AGL), Reber, 1967; visuomotor button press task, Hikosaka, Rand, Miyachi, & Miyashita, 1995). Most studies have investigated whether people implicitly learn a sequence. In particular, some have insisted that people can learn both elements and a higher-order structure of a sequence. For example, Stadler and Neely (1997) showed that the structure of a sequence had a larger influence on learning in the SRT task than the length of that sequence, indicating that some structures tend to be easier to learn than others (see also Cohen, Ivry, & Keele, 1990). Some studies adopting the AGL task suggested that people might implicitly learn fragments or chunks of two, three, or four letters (Servan-Schreiber & Anderson, 1990; Perruchet & Pacteau, 1990). In the visuomotor button press task, Hikosaka et al. (1995)

observed that participants performed slowly and inaccurately when a higher-order sequence was reversed, but individual elements remained identical. Thus, the previous studies pointed to the possibility that people learned certain levels of higher-order structure of a sequence.

Transfer of motor learning refers that some movement controls are learned in one situation and transferred to another situation (e.g., Schmidt & Young, 1987). Experiments with key-pressing tasks have demonstrated transfer between sequences that require different arm or finger movements, suggesting that abstract representations underlie sequence production (e.g., Bapi et al., 2006; Kovacs et al., 2009). Namely, this implies that some representations used for motor execution appear to be independent of the effectors producing the action. Cohen et al. (1990), for example, found that transfer of speed occurs when participants learned a tapping task with their three fingers and then, the same tapping task with their index finger (they were not aware that the learning and transfer tasks were identical sequences due to a distraction task).

Previous studies have reported that people implicitly detect reversed or mirrored structures of musical melodies, even when they are unaware of the structure (e.g., Dienes, Kuhn, Guo, & Jones, 2012). For example, Dienes and Longuet-Higgins (2004) used sequences comprised of twelve musical tones, where the first six tones were randomly generated and the second six tones were altered from the first tones with some specific alternations. During the learning phase, participants were told that the musical melody obeyed some specific rules and in the test phase, they required to answer whether the musical melody followed the rules or not. Results showed that participants who had background experience with atonal music could implicitly detect altered melodies (e.g., reversals and mirrors). Similarly, Kuhn and Dienes (2005) observed that trained participants preferred mirrored melodic structures to non-mirrored structures. Collectively, these results indicate that people could implicitly use the mirror symmetries of learned sequences.

As well as the study of musical melody (e.g., Dienes & Longuet-Higgins, 2004), in the present study, we were interested in whether implicit transfer of visuomotor sequence learning occurred when learned sequences (i.e., visual configuration and finger movement of the sequence)

became mirror symmetries in transfer. In order to investigate the effects of the mirrored structure on implicit transfer in sequential learning, we employed a sequential button press task (e.g., Hikosaka et al., 1995, 1996, 2002; Watanabe et al., 2006, 2010). Hikosaka et al. (1999) summarized that in the visuomotor learning task paradigm, the early trial-and-error stage was controlled and explicit processes and those in the late learning stage were automatic and implicit. The experimental device consisted of 16 light-emitting diode (LED) buttons mounted in a 4×4 matrix while in most studies of the SRT tasks, the device was composed of three or four aligned buttons, which enables us to examine two types of mirror transfer: Vertically mirrored and Horizontally mirrored. In the present study, a fixed visuomotor sequence (which constituted the “hyperset”) of seven triads of button presses (hereafter called “sets”) was generated for each participant. After participants learned the hyperset by trial-and-error, they were required to perform another hyperset, in which the sets were generated by a specific alternation rule. Here, we prepared three alternation rules, with which a visual configuration of the set was vertically mirrored (hereafter called “vertically mirrored rule”), horizontally mirrored (hereafter called “horizontally mirrored rule”), or randomly generated (hereafter called “random rule”).

Method

Participants

120 right-handed participants (68 males, 52 females; mean age = 21.19 years, standard deviation = 2.31) participated in the experiment. All participants had normal or corrected-to-normal visual acuity, normal motor functions, and were naïve to the purpose of this study. All procedures were conducted in accordance with the Declaration of Helsinki.

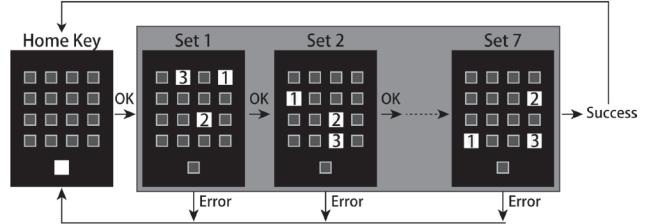
Procedure

We adopted a basic experimental paradigm used in previous studies (e.g., Hikosaka et al., 1995; Watanabe et al., 2010; Figure 1). The experimental device consisted of 16 LED buttons mounted in a 4×4 matrix and another LED button (called the “home key”) at the bottom. Participants used their right index fingers to press the buttons. When participants pressed the home key for 500 ms, three buttons (“set”) turned on simultaneously. Participants were required to press the illuminated buttons in the correct order, which they needed to uncover through trial-and-error. If participants were successful, the LEDs turned off, one by one, and a different set was illuminated, for which the participants were again required to discover the correct order. When participants pressed the wrong button, all LEDs were briefly illuminated, and participants then had to restart from the home key. Seven sets were presented in a fixed order, which we called a “hyperset,” to complete a trial. A trial was considered an error when participants

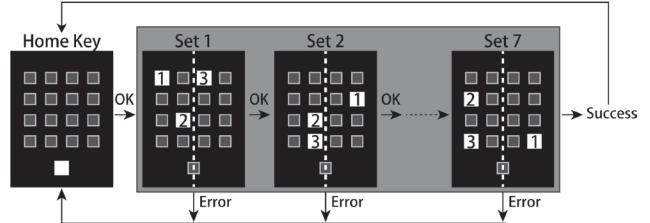
pressed the wrong button in all the sets and successful when participants completed a hyperset, and For example, if participants press the wrong button in Set 5, they would need to start over from the home key. The same hyperset was repeated until participants completed it successfully for 20 trials (called a “block”). Participants were asked to perform the task as quickly and accurately as possible.

We prepared four types of hypersets: “Original,” “Vertically mirrored,” “Horizontally mirrored,” and “Random”. The Original hyperset was randomly generated for each participant. In the Vertically mirrored hyperset, the spatial configurations of the sets were reversed by the vertical axis from the Original hyperset. In the Horizontally mirrored hyperset, the spatial configurations of the sets were reversed by the horizontal axis from the Original hyperset. In the Random hyperset, the new spatial configurations were randomly generated.

Original hyperset



Vertically mirrored hyperset



Horizontally mirrored hyperset

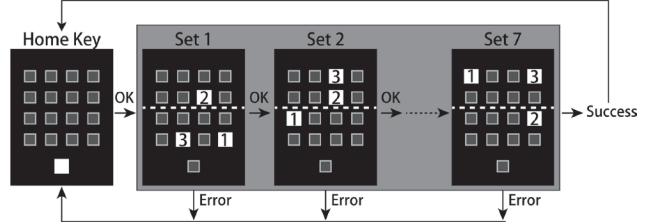


Figure 1. Experimental device and schematic flow of the present study. Participants were instructed to learn the correct order by trial-and-error. The LED buttons were square in shape (10 mm \times 10 mm) and 8 mm apart. Participants were required to discover a correct order by trial-and-error. A trial was considered successful when participants completed a hyperset, and a trial was considered an error when participants pressed the wrong button in all the sets. For example, if participants press the wrong button in Set 2, they would re-start from the home key. A block is finished when participants successfully completed a hyperset 20 times. The Original hyperset was randomly generated for each participant. For each set, the three buttons were defined in ascending order of [1][2][3]. In the Vertically mirrored and Horizontally mirrored

hypersets, all the sets were spatially mirrored with white dashed line, resulting in the Vertically mirrored and Horizontal mirrored sets, respectively from the Original hyperset. The Random hyperset was randomly generated again for each participant, which is different from the Original hyperset. Note that the number shown on the LED button was not displayed during operation.

All participants first performed a block with the Original hyperset and then a block with the Vertically mirrored, Horizontally mirrored, or Random hypersets, which were randomly assigned. The two blocks were separated by a 5-min break. No information was given regarding the alternation rule and, in the second block, participants were instructed that a new hyperset was randomly generated. In order to specifically examine the implicit form of transfer, participants were interviewed after the experiment. In the interview, they were asked how they performed and whether they noticed anything peculiar in the second block. If participants spontaneously reported the mirrored rule, they were excluded from our main analyses. Next, the experimenter explained the mirrored rule to the participants and those who recognized the mirrored rule were also excluded from our main data analyses. Methods for distinguishing explicit knowledge and implicit knowledge are still under debate. Several studies have used subjective measures based on confidence ratings (e.g., Ziori & Dienes, 2006, 2008). Conversely, some studies defined implicit learning that participants were unable to verbalize what they acquired (e.g., Ashby, Alfonso-Reese, Turken, & Waldron, 1998). In this study, we only focused on whether participants noticed the mirrored rule and, therefore, we defined explicit knowledge that participants were able to recognize the mirrored rule.

Data Analysis

As a measure of accuracy, we counted the number of error trials before completing one trial. In order to evaluate speed, we measured the time that had elapsed from the moment the home key was pressed to the moment the third button of the final (7th) set was pressed for each successful trial. Similar parameters have been employed in previous studies and verified (e.g., Watanabe et al., 2006, 2010). We divided the 20 correct trials into five trial sections and calculated mean performance times within each trial section. We defined mean performance times during the fifth section (i.e., 17th to 20th trials) of the first block as a baseline for each individual participant so that we compared the magnitude of transfer among participants who differed on initial performance. We then calculated adjusted performance by subtracting the baseline from performance times during the second block (the Vertically mirrored, Horizontally mirrored, or Random hypersets) and divided by the baseline. This adjusted performance time [$P_{\text{second block}} / P_{\text{baseline}}$] represents the transfer magnitude of participants' performance times. A value more than 1 indicates that the performance time in the second block is faster than that of

the final trial section in the first block (i.e., baseline). Any difference in adjusted performance times indicates a difference in magnitude of transfer among different hypersets in the second block.

Results

Forty participants were assigned for each of the Vertically mirrored, Horizontally mirrored, and Random hypersets. Since nineteen participants in the Vertically mirrored hyperset and seven in the Horizontally mirrored hyperset noticed the mirrored rules, they were excluded from our main analysis. Next, we excluded six participants whose performances in the first block were slower than two standard deviations from each group's average (three participants in Vertically mirrored, two in Horizontally mirrored, and one in Random hypersets). Similarly, we additionally excluded four participants whose performances in the second block were slower than two standard deviations from each group's average (one in Vertically mirrored, one in Horizontally mirrored, and two in Random hypersets). The selection procedure resulted in 17, 30, and 37 unaware participants with acceptable performance, for the Vertically mirrored, Horizontally mirrored, and Random groups, respectively.

We mainly conducted two-way mixed ANOVAs with the five trial sections as a within-subjects factor and the three hypersets as a between-subjects factor, which was called simply "ANOVA" hereafter, and post-hoc tests with the Shaffer's method when performed (called "post-hoc test"). For all hyperset groups, a significant decrease was found in both accuracy and speed measures in the first block, indicating that non-specific learning had occurred (ANOVA; $F(4, 324) > 81.45, p < 0.0001$; for both measures) and there were no differences among the hyperset groups (ANOVA; $F(2, 81) < 0.24, p > 0.78$; for both measures; Figure 2a and 2b). No significant interaction between experimental groups and successful trial sections (ANOVA; $F(8, 324) < 1.24, p > 0.27$; for both measures). These results were accord with those in previous works; the accuracy measure decreased rapidly in the first few completed trials, while the speed measure decreased more gradually (e.g., Watanabe et al., 2006, 2010).

In the second block (transfer block), mean adjusted performance times (i.e., speed) were generally faster (i.e., more transfer was found) in the Vertically mirrored group compared with the Random group (Figure 2c). The ANOVA revealed significant main effects of experimental group ($F(2, 81) = 3.34, p < 0.05$; post-hoc test, Vertically mirrored < Random, $p < 0.05$) and successful trial section ($F(4, 324) = 75.03, p < 0.001$; post-hoc test, 1st > 2nd > 3rd = 4th = 5th section, $p < 0.01$). The interaction between experimental group and successful trial section was not significant ($F(8, 324) = 1.38, p = 0.20$). As for accuracy, the ANOVA revealed significant main effects of experimental group ($F(2, 81) = 12.38, p < 0.0001$; post-hoc test, Vertically mirrored = Horizontally mirrored < Random, $p <$

0.001; Figure 2d) and successful trial section ($F(4, 324) = 361.4, p < 0.0001$; post-hoc test, 1st > the other sections, $p < 0.01$). The interaction between experimental group and successful trial section was also significant ($F(8, 324) = 14.61, p < 0.0001$) and this interaction shows that in the first trial section, the accuracy was higher in the Vertically mirrored and Horizontally mirrored hypersets than in the Random hyperset ($F(2, 81) = 15.06, p < 0.0001$; post-hoc tests, Vertically mirrored = Horizontally mirrored > Random, $p < 0.001$) while in the other trial sections, the accuracy was not different among the experimental groups ($F(2, 81) < 2.09, p > 0.13$; for the other sections).

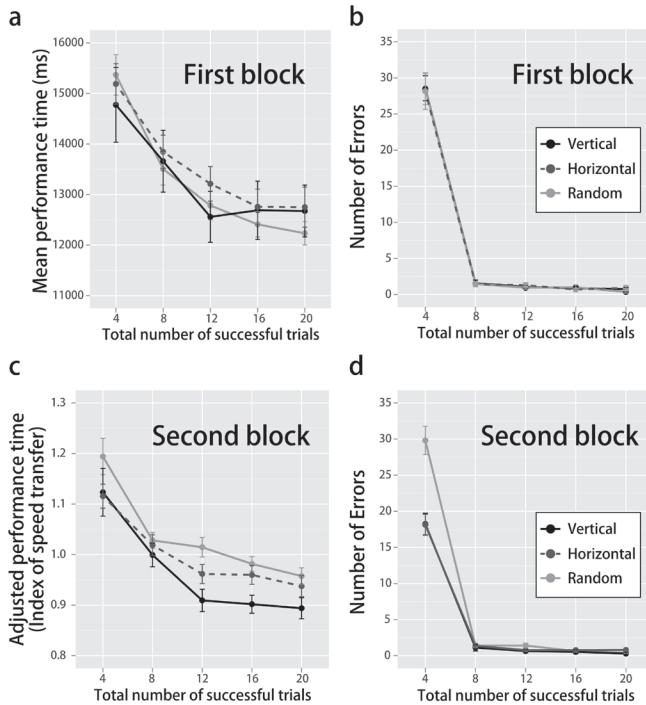


Figure 2. Performance in the first and second blocks. Error bars show the standard errors of the mean. All participants performed the Original hyperset in the first block. (a) Average performance time for successful trials in the first block. (b) Average number of errors before the successful completion of each trial in the first block. (c) Average adjusted performance time for successful trials in the second block. The adjusted performance was computed as follows: $[P^{\text{second block}} / P^{\text{baseline}}]$. (d) Average number of errors before the successful completion of each trial in the second block.

A Pearson's chi-squared test revealed a significant difference in the proportion of participants who noticed the alternation rule between the Vertically mirrored and Horizontally mirrored groups ($\chi^2 = 6.89, p < 0.01$; Vertically mirrored > Horizontally mirrored). Therefore, we additionally examined whether the performances of those groups (aware vs. unaware) in the Vertically mirrored hyperset were different. We excluded two participants in the aware group whose performances in the first block were slower than two standard deviations from the group average (i.e., resulting in 17 aware and 17 unaware participants). In

the first block, we confirmed that performance did not differ between the groups ($F(1, 32) < 2.53, p > 0.12$; for speed and accuracy measures; Figure 3a and 3b). In the second block (transfer block), we found that the accuracy was higher when participants were aware of the alternation rule (Figure 3d). For speed, a two-way mixed ANOVA did not reveal significant main effects of awareness ($F(1, 32) = 2.49, p = 0.12$; Figure 3c) while we observed the significant main effects of successful trial section ($F(4, 128) = 79.63, p < 0.0001$; post-hoc tests, 1st > 2nd > 3rd = 4th = 5th, $p < 0.05$). No significant interaction between group in terms of awareness and successful trial section was not observed ($F(4, 128) = 2.29, p = 0.06$). For accuracy, a two-way mixed ANOVA revealed significant main effects of awareness ($F(1, 32) = 15.74, p < 0.001$; Unaware > Aware) and trial section ($F(4, 128) = 199.73, p < 0.0001$; post-hoc test, 1st > the other sections, $p < 0.0001$), as well as a significant interaction ($F(4, 128) = 18.18, p < 0.0001$). This interaction shows that in the first trial section, the accuracy was higher in the aware group than in the unaware ($F(1, 32) = 19.87, p < 0.001$) while in the other trial sections, the accuracy was not different among the sorted groups ($F(1, 32) < 1.19, p > 0.28$; for the other sections). These results confirmed that once participants obtained the alternation rule (i.e., explicit knowledge), they could clearly perform the hyperset with fewer errors (e.g., Watanabe et al., 2006).

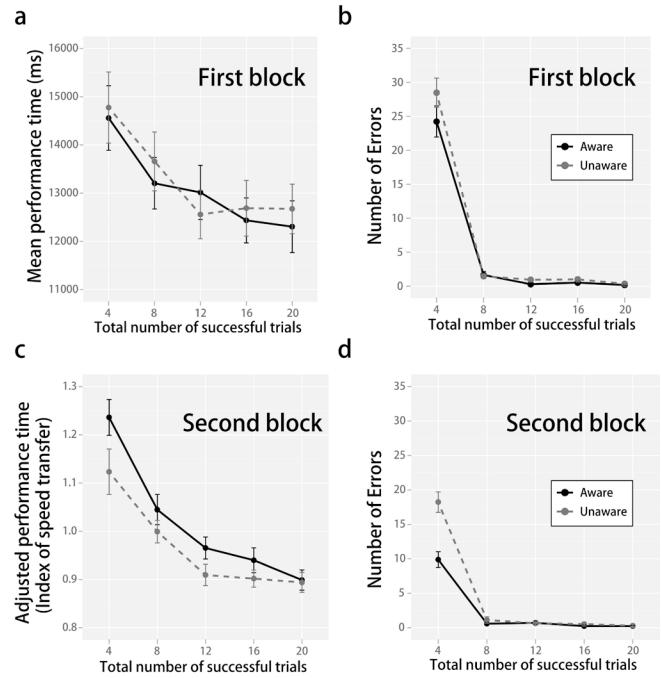


Figure 3. Performance of participants who noticed the vertically mirrored rule ("Aware") and who did not ("Unaware") in the second block. Error bars indicate standard errors of the mean. The adjusted performance was computed as follows: $[P^{\text{second block}} / P^{\text{baseline}}]$. (a) Average performance time for successful trials in the first block. (b) Average number of errors before the successful completion of each trial in the first block. (c) Average adjusted performance times in the second block. (d) Average number of

errors before the successful completion of each trial in the second block.

Discussion

In the present study, we investigated whether a spatially mirrored sequence in visuomotor sequence support implicit transfer of performance in accuracy and speed. We found that (1) both vertically and horizontally mirrored sequence led to transfer of learning in terms of accuracy even when participants did not notice the mirrored rules; (2) vertically mirrored sequence, in addition, led to transfer in terms of performance speed; (3) the proportion of participants who noticed the vertically mirrored rules were significantly higher than the horizontally mirrored rules; and (4) accuracy in the transfer session was significantly higher for the aware group than the unaware group with the vertically mirrored rule.

Previous studies discussed that people who have an experience of playing the piano implicitly discriminated reversed or mirrored structures of musical melodies (e.g., Dienes et al., 2004, 2012), indicating that people can implicitly understand relationships between original and reversed or mirrored sequences of musical tones. In the literature of intermanual transfer (Grafton, Hazeltine, & Ivry, 2002), participants conducted the SRT task with the counting tone task (i.e., this distractor task usually makes participants unaware of the hidden repetition of the sequence) with their left hands in the learning block and subsequently they performed the transfer task with their right hands with the original and mirrored ordered sequence (original sequence, both stimulus sequence and order of response locations remained, but the finger movements were different; mirrored sequence, finger movements in transfer block were identical to those in learning block, but the stimulus location was visually mirrored). Seven out of eight participants were not aware of the repetition of the sequence and the results showed that performance of the original and mirror sequence was significantly better than that of the random sequence. In the present study, the Vertically and Horizontally mirrored hypersets produced the better transfer in terms of accuracy than the Random hyperset. Moreover, the Vertically mirrored hyperset led to better transfer in terms of speed than the Random hyperset. The present study is the first empirical study to show that implicit transfer occurs even when the visual configuration and finger movements of a sequence were consistently vertically or horizontally mirrored. The present results indicate that people implicitly apply their learned representation to the mirrored hypersets.

Most procedural and sequential learning in our daily life possess two stages of processing: the controlled exploration of patterns and the process of automatization after a pattern has been discovered (Anderson, 1982). How sequential learning should be done in order to induce implicit transfer likely has two possibilities; less learning (i.e., remain controlled process) or much learning (i.e., reach

automatic process) leads to implicit transfer. These two possibilities probably depend on whether the automatic process of the learning interferes with transfer; once an automatic process is established, the process can be interference when performing a transfer task because different sequence from learning is required and then, the less learning phase might be better to induce implicit transfer. Conversely, as the automatic process does not require much allocation of attention, the process might give allocation of attention when performing transfer, resulting in implicit transfer. Taken together with previous work (Dienes & Longuet-Higgins, 2004), the results that people could implicitly understand the mirror symmetry might be associated with their automaticity of performance. In the study of music melody, only participants who had played the piano could use the mirrored structure of the music melody, indicating that implicit transfer can occur when cognitive skills (i.e., playing the piano) became automatic process. In the present study, in the first block, the participants completed the hyperset 20 times without errors and in the later learning phase, their performance probably reached at the automatic level (Hikosaka et al., 1999). Thus, these automatic operations likely made an allocation of attention of participants for the transfer task available. For example, Shanks, Rowland and Ranger (2005) showed that performances in the SRT tasks are degraded under double-task conditions, which indicated that implicit learning depends on availability and allocation of attention and is susceptible to the double-task conditions while the learning process was not automatic. Collectively, once a process of task performance reached automatic, the allocation of attention for the learning task is alleviated, resulting in that the allocation of attention for a transfer task became available, which probably made participants possible to implicitly use the mirrored relationship and transfer their obtained representation to the mirrored sequence.

Next, we discuss the differential results between the Vertically and Horizontally mirrored hypersets. We observed implicit transfer of speed only in the Vertically mirrored hyperset, indicating that the vertically mirrored rule might be easier than the horizontally mirrored rule. However, this differs from the Fitt's law (speed-accuracy trade-off; Fitts, 1954) because distances of finger movements were the same between Vertically and Horizontally mirrored hypersets. Then, the present result might pertain to the residual or subthreshold awareness of the mirrored rules. We observed significantly different proportions of participants who noticed the vertically and horizontally mirrored rules. This indicated that the vertically mirrored rule might be easier to notice than the horizontally mirrored rule; sub-threshold awareness of the vertically mirrored order might prime performance within the consistently vertically mirrored sets. The relationship between awareness and difficulty of the task requires to be investigated, but a task of which most people can notice an alternation rule might be easily transferred.

In Watanabe et al. (2006), after a first hyperset was learned, new hypersets were generated by rotating the sets (i.e., entire stimulus configuration) by 0°, 90°, 180°, and 270° (clockwise). Participants were not instructed that the new hypersets were based on the first learned hyperset. Through the experiment, half of the participants spontaneously noticed the regularity of the rotation while the other half did not. Watanabe et al. (2006), then, compared the performances of the participants who were aware and unaware of the regularity and found that those who noticed the regularity could perform the new hyperset more accurately than those who did not notice it while the different performance of speed was not observed. We found that performances of participants who noticed the vertically mirrored rule were more accurate than those who did not notice it. This result was basically accord with Watanabe et al. (2006). Once participants obtained explicit knowledge (i.e., were aware of the hidden rule), they performed the test sequence with fewer errors.

In addition, we compared the performance of the participants who were not aware of the regularity of the Vertically mirrored hyperset and those in the Random hyperset, and found implicit transfer of speed. This point differs from the previous study where no effect of explicit knowledge was found for performance speed with the rotated hypersets. Therefore, the vertical reversal might be a special case in terms of spatial transformation of visuomotor sequences.

In conclusion, in the present study, we investigated whether people could implicitly transfer learned sequence with accuracy and speed to a spatially mirrored sequence. We found that even when participants did not notice the mirrored rules, they showed transfer of learning to the vertically or horizontally mirrored sequence. This result indicates that people could implicitly use the relationship between the learning block and transfer block.

Acknowledgments

This work was supported by Grant-in-Aid for JSPS Fellows and Japan Science and Technology Agency (CREST).

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