Effects of explicit knowledge on transfer of visuomotor sequence learning

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Abstract

Skilled, sequential movements can be acquired explicitly or implicitly. In the present study, we examined the effects of explicit knowledge obtained through instruction or spontaneous detection on transfer of visuomotor sequence learning. In the first session, participants learned a visuomotor sequence by trial and error. In subsequent sessions, the sequence was changed according to specific rules. Some participants received explicit instruction about which specific rules changed, while the others did not. Knowledge of changes via explicit instruction led to slower performance with fewer errors; the sluggishness persisted even in the last phase of transfer learning. On the other hand, knowledge discovered independently by the participants produced slower performance in the initial phase of learning with fewer errors, but their performance speed eventually reached the same level as that of the unaware participants. These results suggest that explicit knowledge may help to reduce errors in the initial phase of visuomotor sequence learning but may interfere with increasing speed, particularly when the knowledge is given rather than found.

Keywords: Sequence learning; Explicit knowledge; Transfer; Interference

Introduction

Skilled sequential movements, such as typing on a keyboard, dialing a phone number, or playing the piano, have key roles in motor behavior in daily life. Many studies have examined how people acquire or improve such sequential behaviors. One of the most common ways to investigate the acquisition of sequential learning is called the Serial Reaction Time (SRT) task (Nissen & Bullemer, 1987). In this task, participants press one of four aligned buttons that are associated with visual stimuli at different positions. In several experimental blocks, a specific sequence was repeated or partly repeated, but participants were not informed of the repetition and did not notice the structure of the sequence (because the sequence was long enough; for example, see Reed & Johnson, 1994; Reber & Squire, 1988). Nevertheless, a reduction in response time occurs without awareness of the sequence structure. In another paradigm, participants first learn a sequence of finger movements and then performance is measured in terms of speed and accuracy (i.e., this paradigm focuses on improvement in performance rather than acquisition) (Karni et al., 1998; Walker et al., 2003).

Explicit knowledge (e.g., whether or not participants notice a repeated sequence and whether or not they were instructed about the sequence explicitly) likely leads to various changes in performance and learning processes in terms of speed and accuracy. In general, implicit learning in the SRT task facilitates response even when participants do not notice a specific sequence (Nissen & Bullemer, 1987). Curran and Keele (1993) assigned participants into three groups: the intentional, more aware, and less aware groups. In the intentional group, the participants were instructed about the repeated sequence before completing the task. The authors defined the participants who were aware of the repeated sequence as the more-aware group and those who were not aware of the sequence as the less-aware group. Participants in that study conducted a single task first, then a dual task. In the single-task blocks, participants were required to press certain buttons when an X appeared on the screen. In the dual-task blocks, a tone sounded several times within the 200-ms stimulus-response interval of the primary task, and the tones were composed of low and high pitches. The participants were instructed to count the number of high-pitched tones while ignoring the low-pitched tones. The results showed that all three groups differed in terms of performance time in the single task: explicit knowledge conveyed intentionally before starting the task led to faster performance during the task. However, in the dual task, the groups did not differ in terms of performance times. They interpreted the results as signifying that awareness affects sequence learning only when attention is fully available; when attention was divided, additional knowledge gained by the aware and intentional groups was not conveyed to the non-attentional mechanism. Similarly, in a previous study (Moisello et al., 2011), participants performed visuomotor sequence learning of a finger opposition task, and response time (i.e., the interval between stimulus presentation and the onset of the corresponding touch) and touch duration (i.e., the contact time between thumb and another finger) were measured for each finger opposition movement of the sequence. The results indicated that sequence learning induced a double-faced effect on motor performance: the participants who were instructed explicitly about a sequence decreased their reaction times, but increased their touch duration, which was regarded as the combination of a sensory phase and a motor preparation phase. Thus, whether explicit knowledge enhances or interferes with performance in sequential learning is still under debate.

In the present study, we examined the effects of explicit knowledge on transfer of visuomotor sequence learning by using another sequential learning paradigm employing instruction or spontaneous detection. The task we employed was a sequential button press task that was originally devised for monkeys as participants (Hikosaka et al., 1995; Rand et al., 1998) and subsequently used on humans (Hikosaka et al., 1995, 1996, 2002; Sakai et al., 1998, 2003) and with which performance improvements in terms of speed and accuracy can be measured separately (Hikosaka et al., 1995, 1996, 2002; Sakai et al., 1998, 2003; Watanabe et al., 2006, 2010). In the first session, participants were required to complete a visuomotor sequence learning task without any instruction (i.e., by trial and error). In the subsequent sessions, the sequence was altered according to a specific rule; either the first and the third responses were switched (reversed) or the first and the second responses were switched (partially reversed). Some participants were explicitly instructed about the specific rule changes before performing the task, while the others did not receive explicit instructions. We also examined whether participants who spontaneously noticed the specific rules without instruction used their knowledge to change their performance.

Method

Participants

Thirty-seven right-handed participants (23 male, 14 female; mean age = 21.02 years, standard deviation = 2.39) participated in the experiment. They were divided into two groups: the explicit-instruction group (14 participants; 8 male, 6 female) and the no-instruction group (23 participants; 15 male, 8 female). All participants had normal or corrected-to-normal visual acuity, normal motor functioning, and were naïve to the purpose of the study. All participants gave written informed consent prior to participation. All procedures were conducted in accordance with the Declaration of Helsinki.

Procedure

The participants performed a sequential button press task, which we call "3 × 7 task." We used essentially the same experimental paradigm as previous studies (e.g., Sakai et al., 2003; Watanabe et al., 2006, 2010). Sixteen LED buttons (10 mm × 10 mm each) were mounted on a panel in a 4 × 4 matrix and were separated from each other by 8-mm spaces. At the bottom of the panel was another LED button, which was used as the "home" key. The participant used his/her right index finger to press the buttons. The home key was turned on at the beginning of each trial. When the participant pressed the home key for 500 ms, 3 out of the 16 target LEDs turned on simultaneously, which we called the "set." The participant was required to press the illuminated buttons in the correct order, which he/she was required to discover by trial and error. Upon success, the LEDs turned off one by one and a different triplet of LEDs was illuminated; the participant was again required to discover the correct order and press the buttons accordingly. When the participant pressed an incorrect button, all the LED buttons were briefly illuminated, a beep sounded, and then the trial was aborted. The participant then had to restart the trial by pressing the home key. A total of seven sets, which we call the "hyperset," were presented in a fixed order for trial completion. A trial was considered successful when the participant completed an entire hyperset (seven sets). The same hyperset was repeated until the participant completed it successfully for 20 trials (called a "block"). Participants were asked to perform the task as quickly and as accurately as possible. We prepared three hypersets, called "original," "reversed," and "partially reversed." The original hyperset was randomly generated for each participant. For each set, the triplet of buttons were defined [1][2][3] in the to-be-pressed order. In other hypersets, the spatial configurations of the sets were not changed, but the sequences of correct button presses were changed. In the reversed hypersets, the participants needed to press the buttons in the order [3][2][1] (i.e., the first and the third buttons were switched). In the partially reversed hypersets, they needed to press the buttons in the order [2][1][3] (i.e., the first and second buttons were switched).

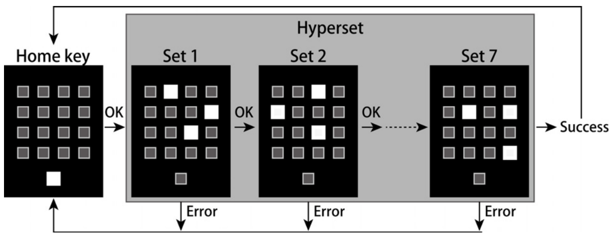

Figure 1. Schematic flow of the experiment. Participants were instructed to learn the correct order of button presses by trial and error. The LED buttons were square-shaped (10 mm × 10 mm) and 8 mm apart.

The participants conducted one session using the original hypersets, followed by two sessions using the reversed and the partially reversed hypersets. The order of the final two test sessions was counterbalanced across participants. The three sessions were separated by a 5-minute break. In the explicit-instruction group, the rules of the reversed and the partially reversed orderings were explicitly told to participants before the beginning of each session. In the no-instruction group, they were told that the sets were randomly assigned. For the no-instruction group, the participants were asked whether they had noticed anything peculiar after each session. If the answer was yes, then they were questioned further and asked if they had noticed the rules of changes in the hypersets. Then, participants who noticed the rules were defined as the aware group, and those who did not notice the rules were defined as the unaware group. Hence, we eventually had three groups: the explicit, aware, and unaware groups.

Data Analysis

We used two measures to assess the accuracy and speed of performance in each block. As a measure of accuracy, we counted the number of errors before correctly completing each trial. To evaluate speed, we measured the time that 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 were employed in previous studies and proved to be useful (Hikosaka et al., 1999, 2002; Watanabe et al., 2006, 2010). We calculated average performance using each hyperset by assessing five sections of cumulative successes (i.e., 1st to 4th, 5th to 8th, 9th to 12th, 13th to 16th, and 17th to 20th). For the reversed and partially reversed hypersets, we normalized performance time by using each participant's performance in the last section (i.e., mean performance from the 17th to 20th trials) in which the original hypersets were used as the baseline. Mean performance times of the five sections using the reversed and partially reversed hypersets were subtracted from performance times at baseline.

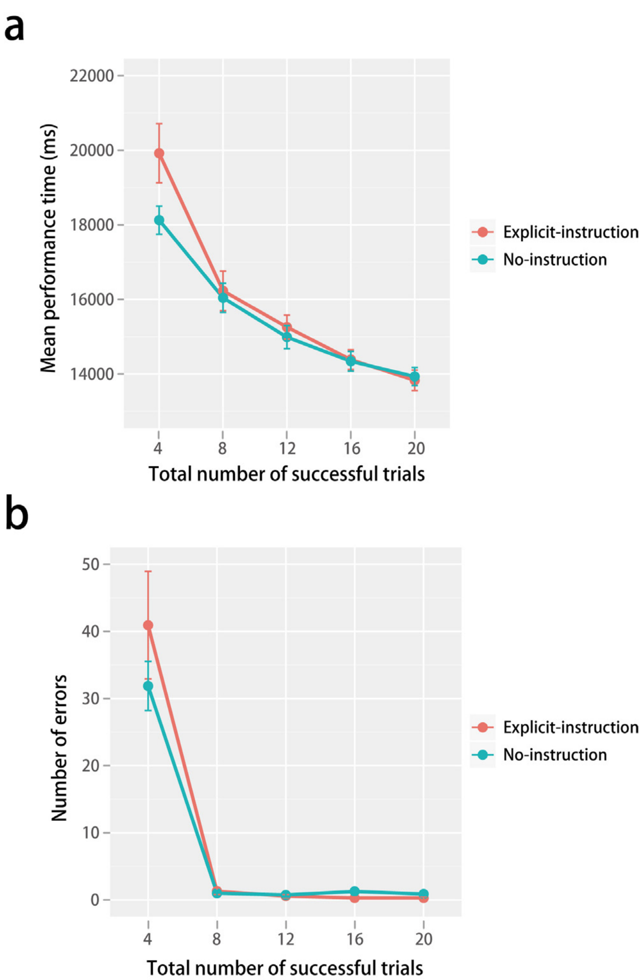

Figure 2. Performance changes in the first block with the learning hyperset. Error bars show the standard error of the means. (a) Average performance time for successful trials. (b) Average number of errors before the successful completion of each trial.

Results

Learning session with original hyperset

A significant decrease was found in both the accuracy (the number of completion failures) and speed measures (averaged completion time for successful trials) in the first session with the original hyperset irrespective of the group (Figure 2), indicating that learning did occur [ANOVA; $F(4, 140) = 51.44$, $p < 0.0001$; for both measures]. The accuracy measure decreased rapidly in the first few completed trials while the speed measure decreased more gradually. These results are in accordance with those of previous studies (Hikosaka et al., 1995, 1996, 2002; Sakai et al., 1998, 2003; Watanabe et al., 2006).

Comparison between explicit-instruction and no-instruction groups

First, we examined the effects of explicit instruction on the 3 × 7 task. Explicit instruction slowed down performance. The partially reversed hypersets also slowed performance. A three-way ANOVA revealed significant main effects of instruction ($F(1, 35) = 13.84$, $p < 0.001$; explicit > no-instruction), hyperset ($F(1, 35) = 40.78$, $p < 0.0001$; partially reversed > reversed), and trial section ($F(4, 140) = 145.85$, $p < 0.0001$; post hoc, Shaffer's method, 1st > 2nd > 3rd > 4th > 5th). A significant interaction was also found between instruction and trial section ($F(4, 140) = 30.34$, $p < 0.001$).

On the other hand, explicit instruction had a positive effect on the accuracy measure, but only for the first sections using the reversed and partially reversed hypersets. A three-way ANOVA revealed significant main effects of instruction ($F(1, 35) = 8.35$, $p < 0.01$; no-instruction > explicit), hyperset ($F(1, 35) = 12.44$, $p < 0.01$; partially reversed > reversed), and trial section ($F(4, 140) = 29.15$, $p < 0.001$; post hoc, Shaffer's method, 1st > all other sections). A significant interaction was also found between instruction and trial section ($F(4, 140) = 12.33$, $p < 0.001$).

Comparison between aware and unaware groups

Among 23 participants in the no-instruction group, 8 participants spontaneously noticed the specific rules of both the reversed and the partially reversed hypersets during the experiment; hence, they were classified as the "aware" group. The other 15 participants did not notice either of the rules during the experiment and were classified as the "unaware" group.

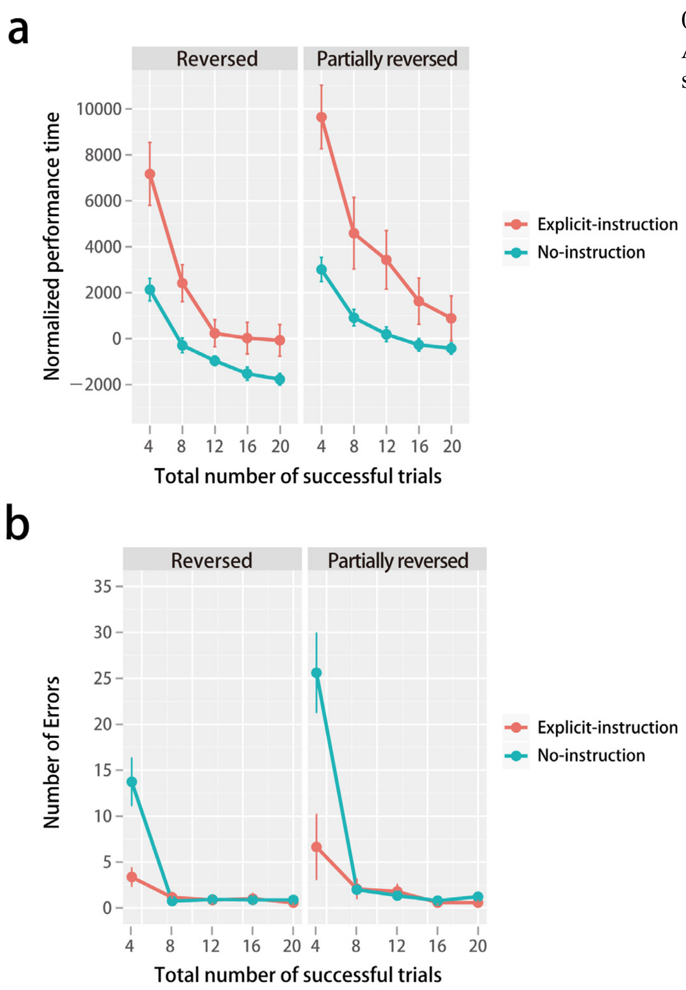

Figure 3. Performance of the explicit and no-instruction groups in the second and third sessions using the reversed and partially reversed hypersets. Error bars show the standard error of the means. (a) Average normalized performance times. (b) Average number of errors before the successful completion of each trial.

Figure 4a shows the mean normalized performance times of the aware and unaware groups. The aware group exhibited slower normalized performance times when using both the reversed and partially reversed hypersets. A three-way ANOVA revealed significant main effects of instruction ($F(1, 21) = 4.99$, $p < 0.05$; aware > unaware), hyperset ($F(1, 21) = 16.83$, $p < 0.001$; partially reversed > reversed), and trial section ($F(4, 84) = 116.51$, $p < 0.0001$; post hoc, Shaffer's method, 1st> 2nd > 3rd > 4th = 5th). A significant interaction between instruction and trial section was also revealed ($F(4, 84) = 10.34$, $p < 0.0001$). The number of errors observed was higher in the aware group's first section compared to the unaware group's first section (Figure 4b). A three-way ANOVA revealed significant main effects of instruction ($F(1, 21) = 8.43$, $p < 0.01$; unaware > aware), hyperset ($F(1, 21) = 13.49$, $p < 0.01$; partially reversed > reversed), and trial section ($F(4, 84) = 35.20$, $p < 0.001$; post hoc, Shaffer's method, 1st > all other sections). A significant interaction between instruction and trial section was also found ($F(4, 84) = 8.87$, $p < 0.001$).

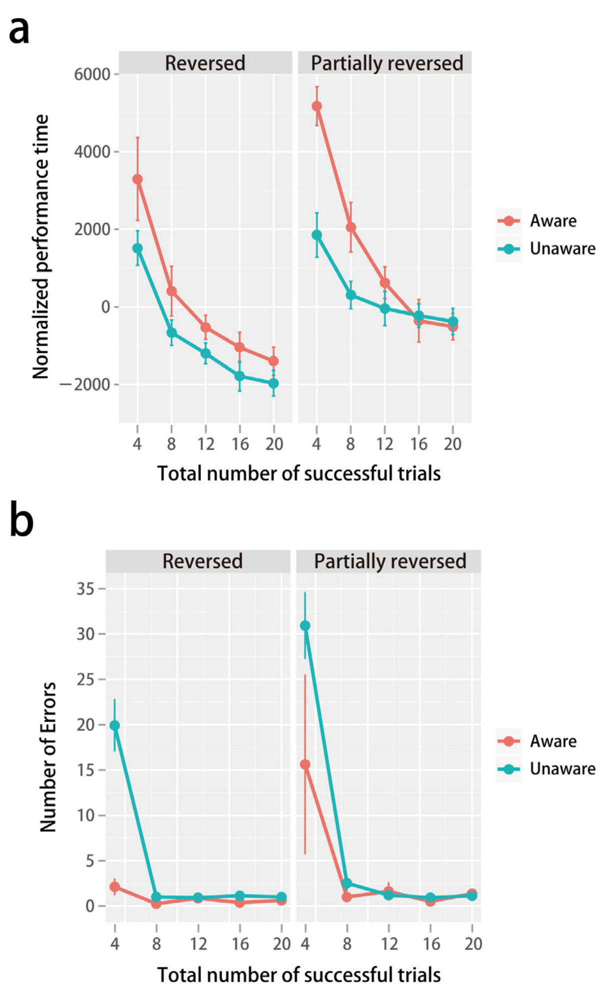

Figure 4. Performance of the aware and unaware groups in the second and third sessions using the reversed and partially reversed hypersets. Error bars show the standard error of the means. (a) Average normalized performance times. (b) Average number of errors before the successful completion of each trial.

Discussion

In the present study, we examined the effects of the acquisition of explicit knowledge though instruction or spontaneous detection on transfer of visuomotor sequence learning. Knowledge of changes via explicit instruction led to slower performance with fewer errors, and this sluggishness persisted even in the last phase of learning. On the other hand, knowledge discovered spontaneously by participants produced slower performance in the initial phase of learning with fewer errors, but performance speed tended to peak at the same level as that of the unaware participants (using the partially reversed hyperset). These results suggest that explicit knowledge may help to reduce errors in the initial phase but may interfere with increasing speed, particularly when the knowledge is given rather than found.

The participants who spontaneously noticed the presence of the rules showed slower performance than those who did not notice the rules in the initial phase of the session, which they performed with fewer errors. The lack of influence of explicit knowledge on the later stages of learning is consistent with the two-loop model of visuomotor sequence learning (Nakahara et al., 2001) and with previous studies (Watanabe et al., 2006). Watanabe et al. (2006) examined the influence of explicit knowledge of stimulus configuration (workspace) in visuomotor sequence learning, and their experimental paradigm was essentially the same as that of the present study. After the first session (i.e., learning a specific visuomotor sequence by trial and error), the workspace was rotated for the second session without notifying the participants. It is noteworthy that participants who noticed the rules of rotation did not improve in terms of performance time, though they were able to use their explicit knowledge of the rotation. In the task employed in the present study, explicit knowledge of the sequence is critical for performing and proceeding through the task (as in other learning paradigms that involve explicit instructions of sequences; Jueptner et al., 1997a, 1997b; Karni et al., 1995). For other types of procedural learning, including rotary movement pursuit and mirror tracing, explicit knowledge has little effect on the accuracy and/or speed of task performance (e.g., Heindel et al., 1989). Differences in the necessity of explicit knowledge may explain this discrepancy between results.

Slower performance by participants who received explicit instruction might appear contradictory with the results of previous studies. In the SRT task, explicit knowledge given before the task could lead to faster performance during the task (Curran & Keele, 1993). One possible interpretation is that the role of explicit knowledge may differ in different paradigms of sequential learning because spatial sequence is learned by trial and error in the 3 × 7 task, whereas spatial sequence is defined in a stimulus-driven way in the SRT task (Curran & Keele, 1993; Nissen & Bullemer, 1987; Willingham et al., 1989). Another possible interpretation is that the effects of explicit knowledge may depend on the demands of the task. Curran and Keele (1993) showed that explicit knowledge of a to-be-learned sequence led to faster performance in a single task but not in a dual task, and they implied that explicit knowledge facilitated sequence learning only when attention was fully available. In the present study, the participants were required to complete a task without instruction first, and then the participants in the explicit-instruction group conducted the task with explicit knowledge of the rule changes. In other words, the participants were required to maintain the prior order and the instruction to reverse the original hyperset, whereas participants in the SRT task were required only to retain information about which button to press. This difference also might be related to the capacity limit of working memory. Previous work showed that if an individual is asked to hold words in working memory and to judge whether a probe word was one of the retained words, response time increased with memory set size (e.g., McElree & Dosher, 1989; Sternberg, 1969). In the present study, the performance speed of the explicit-instruction group did not reach an equal level to that of the no-instruction group even in the final phase. Thus, explicit knowledge given by another person thoroughly hindered performance speed for the duration of the experiment. As for individual differences in hindrance, participants who have high working memory capacities might not be influenced, and vice versa. Clarification of this proposal would require further investigation.

The present findings can be exemplified by a more familiar hypothetical case. Assume that you are dialing a phone number that you know well. In this case, you can dial it quickly. If you are asked to dial a new phone number that is actually the reverse of the well-known phone number, and you do not notice this fact, you will become able to dial it fast. If you notice that the new phone number is the reverse of the well-known phone number on your own, it would slow your learning, but you will eventually be able to dial the new number quickly. However, if you are explicitly asked to dial the reverse of the well-known phone number, you will not be able to dial the reversed phone number as quickly as the original phone number. It is noteworthy that in the final phase, the performance speed in the explicit-instruction group did not reach the same level as that in the no-instruction group. This could be because attentional resources need to be partly devoted to holding explicit knowledge, which reduces the efficacy of learning. However, further investigation is warranted in order to elucidate how explicit knowledge interferes with learning.

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