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Anticipation measures of sequence learning: manual versus oculomotor versions of the serial reaction time task

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ABSTRACT
The serial reaction time (SRT) task has generated a very large amount of research. Nevertheless the debate continues as to the exact cognitive processes underlying implicit sequence learning. Thus, the first goal of this study is to elucidate the underlying cognitive processes enabling sequence acquisition. We therefore compared reaction time (RT) in sequence learning in a standard manual activated (MA) to that in an ocular activated (OA) version of the task, within a single experimental setting. The second goal is to use eye movement measures to compare anticipation, as an additional indication of sequence learning, between the two versions of the SRT. Performance of the group given the MA version of the task ($n = 29$) was compared with that of the group given the OA version ($n = 30$). The results showed that although overall, RT was faster for the OA group, the rate of sequence learning was similar to that of the MA group performing the standard version of the SRT. Because the stimulus-response association is automatic and exists prior to training in the OA task, the decreased reaction time in this version of the task reflects a purer measure of the sequence learning that occurs in the SRT task. The results of this study show that eye tracking anticipation can be measured directly and can serve as a direct measure of sequence learning. Finally, using the OA version of the SRT to study sequence learning presents a significant methodological contribution by making sequence learning studies possible among populations that struggle to perform manual responses.

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KEYWORDS
Sequence learning; Eye movements; Serial reaction time; Anticipation

The serial reaction time (SRT) task (Nissen & Bullemer, 1987) is one of the most common tasks used to study implicit motor sequence learning. Sequence learning is reflected in two ways: first, by reduced reaction time (RT) across training blocks, and, second, by increased RT when presented with a block that contains a different sequence. The latter is interpreted as a purer measure of sequence learning while the former is interpreted to include other general aspects of the task such as stimulus response (S–R) mapping (Helmuth, Mayr, & Daum, 2000). This task has generated a very large amount of research, but nevertheless there is an ongoing debate as to the exact cognitive processes underlying implicit sequence learning. Some theories emphasize *stimulus* learning (e.g., Clegg, 2005), *response* learning (e.g., Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004), or *stimulus–response* (S–R) learning (Schumacher & Schwarb, 2009; Willingham, Nissen, & Bullemer, 1989; for review see, Schwarb & Schumacher, 2010, 2012). In their recent review, Schwarb and Schumacher (2012) concluded that the S–R rule hypothesis best accounts for the inconsistent findings in the literature.

One of the limitations of the SRT is that it is dependent on manual responses. Therefore clinical populations with motor impairment (e.g., Parkinson's disease) achieve lower scores on this task that do not necessarily reflect a pure sequence-learning deficiency. The same may apply to children or elderly participants with documented slower RTs

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(Albouy et al., 2008; Helmuth et al., 2000). Several previous attempts have been made to bypass this limitation (Smith & McDowall, 2006; Vakil, Kahan, Huberman, & Osimani, 2000).

Recently, numerous studies used an eye tracker in an attempt to study sequence learning while avoiding manual responses. Marcus, Karatekin, and Markiewicz (2006) measured eye movements while participants observed the stimulus for 1000 ms in one of four spatial locations. Learning was evident by the fact that the number of eye movements towards the expected spatial location increased as a function of rehearsing the repeated sequence. Similarly, Albouy et al. (2006) recorded the eye movements of participants who were asked to follow a dot that moved to a different location every 550 ms. Here too, the results showed that ocular sequence learning is possible. The oculomotor version of the SRT used in these two studies is similar to the standard-manual version of the task in that it requires participants to learn a repeated sequence of changes to the spatial location of a stimulus. However, it differs in at least one important way, namely that unlike the standard SRT in which the participants respond to the stimuli as they appear at various locations, in the oculomotor version, participants observe and follow the changing locations of the stimuli. Thus, unlike the standard version in which the participant's response triggers the move to the next location, in the oculomotor version, stimuli move at a predetermined rate that is independent of the participant's response. Nevertheless, it should be noted that there are some reports in the literature of similar versions of the task that used a fixed presentation rate (e.g., Frensch & Miner, 1994; Schumacher & Schwarb, 2009) and yielded similar results.

Kinder, Rolfs, and Kliegl (2008) also studied oculomotor sequence learning, but unlike previous studies, the stimulus position changed as a result of the participant's oculomotor response as indicated by fixation on the correct location for at least 90 ms. Their results replicated the findings typically observed using the standard manual SRT. The authors interpreted their results to be inconsistent with the claim made by Willingham et al. (1989), namely that what is learned in the SRT is the S–R association, 'S' being the stimulus presented on the screen and 'R' being the manual response on the keyboard. The reason is that in their paradigm, S–R association, stimulus presentation, and oculomotor response are actually identical, and thus the association is automatic and preexists prior to training. Kinder et al. (2008) suggest that what is learned in the oculomotor paradigm of the SRT is 'either a speed-up in spatial orientations and/or oculomotor responses' (p. 204). However, the S–R theory can be interpreted differently. Willingham et al. (1989) state that what is learned in the SRT task is a sequence of S–R mappings. To quote Deroost and Soetens (2006), 'learning is represented as a sequence of stimulus–response bounds' (p. 450). Furthermore, Kinder et al. (2008) assert that the S–R are identical in the oculomotor version of the SRT task. It is difficult to claim that the dot on the screen and the oculomotor response are identical even though the pairing in this case is automatic. Thus, according to this interpretation of the S–R theory, the fact that S–R pairing is automatic in oculomotor sequence learning does not prevent the *sequence* of these S–R pairs from being learned.

It has been demonstrated that we continuously generate predictions (Bar, 2009), particularly during rule learning, which includes sequence learning, as indicated by improved anticipation (Dale, Duran, & Morehead, 2012). In tasks such as the SRT, reduced RT is interpreted to reflect improved anticipation of the spatial location in which the next stimulus is expected to appear. Thus, reduced RT is actually indirect evidence of improved anticipation. In an attempt to measure anticipation directly, Dale et al. (2012) used a manual spatial-position tracking task. Movement of the computer-mouse cursor toward the target was interpreted as a direct measure of anticipation.

Although previous studies measured sequence learning using oculomotor activation (OA), they did not compare it directly to standard manual activation (MA) of the task. Furthermore, to the best of our knowledge, none of the previous studies measured OA and MA sequence learning and measures of anticipation as a direct indication of learning within a single experiment. Thus, in this study, performance on two versions of the SRT was compared, as one group performed the standard MA, and the other group performed the OA version of the task. All participants' eye movements were recorded. Before the appearance of each target, a blank slide that displayed the four squares without a target appeared for 500 ms. Eye movements on this slide were used to measure anticipation—that is, whether the eyes moved towards the expected position of the next target.

Hence, the objectives of this study are twofold. First, in an attempt to elucidate the underlying cognitive processes that enable sequence acquisition, RT will be compared during sequence learning in the MA versus OA versions of the SRT within a single experimental setting. Second, eye movement measures in the two versions of the SRT were used to compare anticipation rates as an additional indication of sequence learning. A paradigm of this kind allows us to compare indirect (i.e., RT) and direct (i.e., eye movements) measures of sequence learning, as well as anticipation, within a single experiment. Such findings could contribute to our understanding of the underlying cognitive processes in sequence learning.

EXPERIMENTAL STUDY

Method

Participants

Participants were divided into two groups. The MA group consisted of 29 young adults (11 males, mean age: 23.8 years, range 18–32 years), and the OA group consisted of 30 young adults (11 males, mean age: 23.3 years, range 20–32 years). Seven additional participants were excluded due either to their inability to complete the experiment as a result of poor calibration, or extreme scores. Participants were undergraduate students, who either took part in the experiment as part of their course credit or were paid 30 NIS (~10 $US). The study was approved by the ethics committee of the Psychology Department in Bar-Ilan University, and each participant gave written informed consent.

Stimuli

Stimuli consisted of five slides, each with a resolution of 1400 × 1050 pixels. Stimuli included four white squares arranged in a diamond shape on a grey background. A black dot (indicating the target) appeared in one of the four white squares. The size of each square was 6 × 6 cm, and the diameter of the dot was 1.5 × 1.5 cm (see Figure 1a). This layout of SRT stimuli is based on Kinder et al. (2008). Four slides included a target image, and the fifth slide did not display a target (this slide is referred to as the blank slide used to measure anticipation).

Tools

The SRT programmed in the SMI Experiment Center™ (SensoMotoric Instruments, Teltow, Germany) was used for the OA group. For the MA group, E-Prime 2.0 was used. Eye movements were recorded by the SMI iView 250 RED Eye Tracker, sample rate: 250 Hz. The stimuli were presented on an LCD computer screen (size 47 × 29 cm; resolution 1680 × 1050 pixels). The recording device was installed beneath the screen. Participants were seated in front of the screen, approximately 60 cm away from it.

Procedure

Participants were randomly assigned to one of the two versions of the SRT, either MA or OA. In both, a black dot (the target) appeared in one of four white squares arranged in a diamond shape (see Figure 1a). In the MA SRT task, round black stickers were placed on the 8, 4, 2, and 6 keys on the number pad on the keyboard, to correspond with the up, left, down, and right directions, respectively. The slide containing the target remained visible until one of the four keys was pressed, and then the target disappeared, otherwise it was displayed for 3000 ms. The participants in the MA task were instructed to press the corresponding button on the keyboard using only the index finger of their dominant hand. Before each slide with a target appeared on the screen, a blank slide with four empty squares (without a target) appeared for 500 ms (i.e., the anticipation slide).

In the OA SRT task, the participants were instructed to find the target and to look at it until it disappeared. The slide was oculomotor activated, so that it was presented until the participant fixated on the square that contained the target either for 100 ms, or for 1000 ms if the participant did not fixate on the target for the required duration. The experiment consisted of eight blocks with 30-s intervals in the MA task and one-minute intervals between each block in the OA task. The extra time was needed in the OA task in order to calibrate the device before each block. This was necessary because, unlike the MA task, eye movements must be highly calibrated in the OA task in order to detect and activate the area of interest. However, it should be noted that the precision of the eye movement calibration in the MA task was constantly monitored, and the experiment was stopped if a deviation was detected. Each experimental block consisted of a 12-element sequence repeated nine times (see Figure 1b). Thus, each block was composed of 108 trials. There were six learning blocks (Block 1 to Block 6), an interference block with a different sequence (Block 7), and an additional block with the original sequence (Block 8). Each block began the sequence from a different point. The sequences were adapted from Gabriel et al. (2013), and no

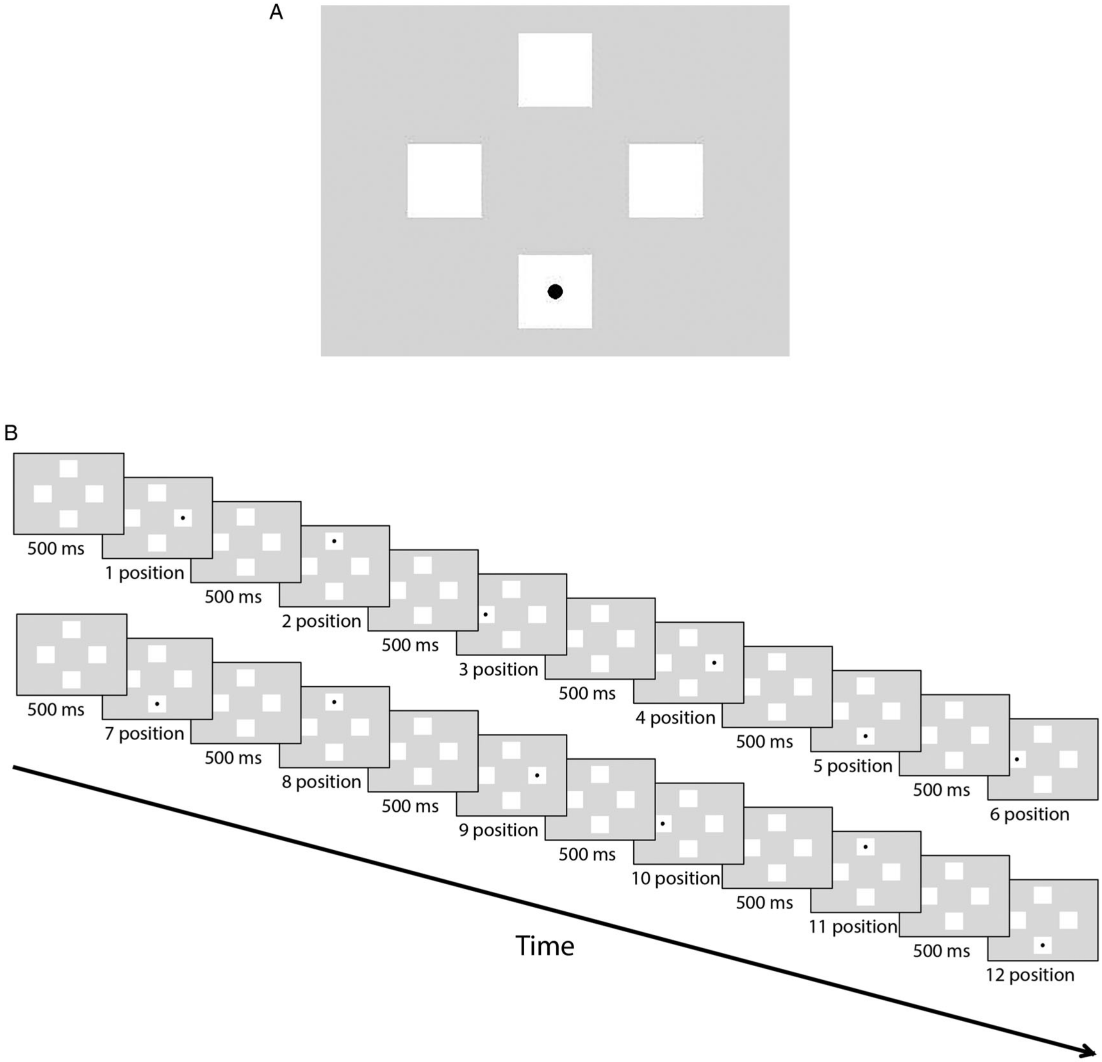

Figure 1 . (A) Illustration of the serial reaction time (SRT) task. An example of a target slide. In the ocular activated (OA) version of the SRT this slide was activated by 100 ms of fixation on the white square. In the manual activated (MA) version of the SRT the slide was activated by pressing the corresponding key on the keyboard. (B) Illustration of the SRT. One of the sequences used in the experiment design of the SRT. Participants were presented with one of the sequences for Blocks 1–6 and Block 8 and with the alternative sequence for Block 7, the interference block.

first-order predictive information was provided (i.e., each location is preceded by the same location only once—12, 13, 14, 21, 23, etc.). Both contained one reversal (Sequence 1: 1–2–1; Sequence 2: 3–2–3). The order of the sequences was counterbalanced—that is, for half of the participants the learning sequence was 3–4–2–3–1–2–1–4–3–2–4–1, and the interference sequence was 3–4–1–2–4–3–1–4–2–1–3–2, as can be seen in Figure 1b. For the other half, the order was reversed. Each number in the sequence was matched with one of the four squares: 1, 2, 3, and 4 to correspond with down, left, right, and up, respectively.

All of the participants' eye movements were recorded using the SMI iView 250 RED Eye Tracker. In the OA task, calibration was done at the beginning of each block, and in the MA task, calibration was performed once at the beginning of the task. Calibration was done using a standard 9-point grid for both eyes. In the OA group, a 4-point grid was used for validation after each calibration trial, and the quality of the calibration was automatically evaluated at the beginning of each block. The system demanded a new calibration if it did not identify a gaze within an unseen 0.5° × 0.5° square surrounding the fixation point, for 2 s.

Explicit learning and generate task

At the end of the eighth block, all participants were presented with an explicit task. This part was identical for both groups and was programmed using the SMI Experiment Center™ (SensoMotoric Instruments, Teltow, Germany). First, participants were asked two questions to assess awareness of the repeated order. The questions were shown on the screen, and participants answered by selecting yes or no using the mouse. The first question explicitly evaluated whether participants were aware of the repeated order. The question was 'Did you notice anything special about the experiment?' (One point was given for a 'yes'). It was then followed by a more specific question 'Did you notice any patterns during the experiment?' (One point was given for indications that there was a repeated sequence). Next, in the generate task, participants in both groups were reminded that the sequence of positions would be run on the screen twice. We actually allowed 26 trials and ignored the first two, assuming that they would be purely chance. Then the sequence was presented with each slide shown for 700 ms. Afterwards, when each slide containing a target was displayed, participants were asked to look at the location at which the next target was supposed to appear. The square that would contain the next target was eye-activated, so that the next slide appeared only after the participant looked at the correct location for 200 ms. When participants looked at the wrong location, they were asked to try a different location until the new target appeared. A blank slide was displayed for 500 ms between all slides containing targets.

Data analysis

Data were registered using BeGaze™ (SensoMotoric Instruments, Teltow, Germany) to measure eye movements for both groups and behavioural responses for the OA group and E-prime (behavioural responses for the MA group). Three phases of performance were analysed separately: learning (Blocks 1 to 6), interference (Block 6 vs. Block 7), and recovery from Interference (Block 7 vs. Block 8). In addition, performance in the interference block was compared with baseline performance (Block 7 vs. Block 1). Two dependent measures were used—speed (RT to the slide with the target) and percentage of correct anticipations (to the anticipation slide).

Results

Speed: RT

In the MA group, RT was calculated using RTs generated from the E-Prime program, which recorded the participants' key presses. In the OA group, RT was calculated using the 'entry time'—namely, elapsed time until the first fixation on the correct square in which the target appeared. The mean of the medians (of a 12-item sequence) of RT per block (i.e., 108 trials) was analysed. Figure 2 presents the mean of the medians of RT as a function of Blocks 1 to 8 of the SRT for both groups. Three different measures of sequence learning were analysed. The first, *learning blocks,* reflects the learning rate as expressed by the reduction of RT across the first six learning blocks. The second, *transfer* (Block 6 vs. Block 7), reflects the cost of shifting to a new sequence, and the third, *recovery from interference* (Block 7 vs. Block 8), reflects the facilitation of performing the learned sequence even after interference.

Learning blocks. Mixed-design analysis of variance (ANOVA; 2 × 6) was used to analyse the effects of the between-subjects condition factor of group (OA and MA) and the within-subjects factor of learning (Blocks 1–6). The analysis of the mean of median RT of the two groups in the first six blocks, as shown in Figure 2, showed that the MA group was slower than the OA group, $F(1, 56) = 197$, $p < .01$, effect size (ES) = 0.78. There was a significant reduction in RT over Blocks 1–6, $F(5, 280) = 39.94$, $p < .01$, ES = 0.42. The group by learning interaction reached significance, $F(5, 280) = 4.92$, $p < .01$, ES= 0.81. In order to detect the source of the interaction, and based on the trend presented in Figure 2, we analysed the first two and the last four blocks separately. In addition to the learning effect, an interaction between learning and group was found only in the analysis of Blocks 1–2 and not in the analysis of Blocks 3–6 [$F(1, 57) = 8.24$, $p < .01$, ES = 0.26; $F(3, 168) = 0.67$, $p = .62$, ES = 0.01, respectively]. These results suggest that although the overall speed of the OA group was faster than that of the MA group, the learning rate of the latter was steeper only in the early phase of the learning process.

Interference. Mixed-design ANOVA (2 × 2) was used to explore the effect of group as above and the within-

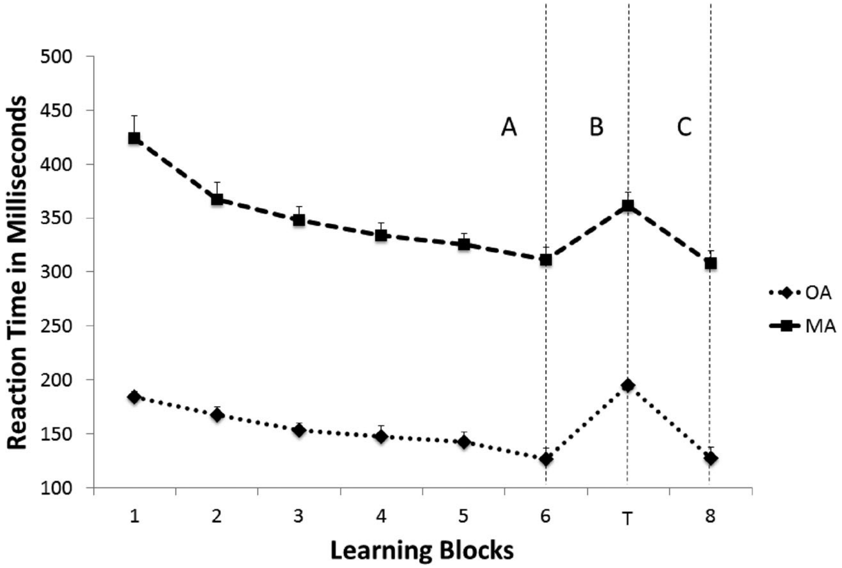

Figure 2. The mean of the median reaction time (RT; and *SE*) of the manual activated (MA) and ocular activated (OA) groups in the eight serial reaction time (SRT) task blocks. The seventh block contains an interference sequence. For the MA group, RT was measured as the time before the participant pressed the correct button. For the OA group, RT was measured as the time until the first fixation on the square containing the target.

subjects factor of interference (Block 6 vs. Block 7). As shown in Figure 2, the MA group was slower than the OA group, *F*(1, 57) = 185.52, *p* < .01, ES = 0.77. Interference effect reached significance as well, F(1, 57) = 84.59, *p* < .01, ES = 0.6. The group by interference interaction did not reach significance, *F*(1, 57) = 1.88, *p* = .18, ES = 0.03. These results indicate that the interference affected both groups equally.

Recovery from interference. Mixed-design ANOVA (2 × 2) was used to explore the effect of group as above and the within-subjects factor of recovery from interference (Block 7 vs. Block 8). Group main effect reached significance, *F*(1, 57) = 190.33, *p* < .01, ES = 0.77. Recovery from interference effect reached significance as well, *F*(1, 57) = 85.55, *p* < .01, ES = 0.6. As can be seen in Figure 2, the overall performance time in Block 7 was slower than that in Block 8. The group by recovery from interference interaction did not reach significance, *F*(1, 57) = 1.11, *p* = .3, ES = 0.02.

Comparison between baseline and interference. Mixed-design ANOVA (2 × 2) was used to explore the effect of group as above and the within-subjects factor of interference (Block 1 vs. Block 7). Group main effect reached significance, *F*(1, 57) = 173.90, *p* < .01, ES = 0.75. The difference between baseline (Block 1) and the interfering block (Block 7) reached significance as well, *F*(1, 57) = 9.59, *p* < .01, ES = 0.14. This finding should be interpreted cautiously because of the significant group by interference interaction, *F*(1, 57) = 19.11, *p* < .01, ES = 0.25. As can be seen in Figure 2, while RT in the interference block in the OA group returned to baseline, performance in the interference block for the MA group was still significantly better than baseline.

It should be noted that oculomotor RTs were collected from the MA group throughout the task as well. This enabled comparisons between the oculomotor RTs of the MA and the OA groups. Both groups displayed a very similar pattern of results (*p* > .05), indicating that manual responses do not affect eye movement patterns.

Percentage of correct anticipations

This paradigm was designed to serve as an implicit measure of sequence learning. It is assumed that shifting the gaze to the anticipated location prior to the appearance of the target is an implicit indication that the particular component of the sequence has been learned. Anticipation was evaluated by detecting the transition of the participant's gaze to the correct subsequent position during the presentation of the blank slide (that followed each target slide). We used the function 'area of interest' in the BeGaze program and enlarged the squares into a triangle, so that four triangles covered the four squares and the centre point of the screen (see Figure 3).

During the 500 ms in which the blank slide was presented, the participant's gaze (measured by the location of the fixations) could remain in the same location in which the previous target appeared, move to *one* of the other three locations, or move to *more* than one location. It was found that across all of the blocks, participants' gazes moved to only one location in most of the trials (73.87%; see Figure 4). In 22.92% of the trials, gaze remained in the same location, and only in a negligible percentage of trials (3.19%) did participants' gaze go to more than one location. Therefore, in order to study the anticipation pattern, we analysed only the trials in which participants moved their gaze towards a different location. We set an anticipation score of '1' for the slides in which there was at least one fixation on the correct location (where the next target was going to appear) and a '0' score for fixations on one of the incorrect locations.

We then counted the number of correct anticipations per sequence and calculated the average for nine sequences per block (similar to the way RT was calculated). This established the percentage of correct anticipations score for each block for all participants. Figure 5 presents the average percentage of correct anticipations as a function of learning blocks in the SRT for both groups.

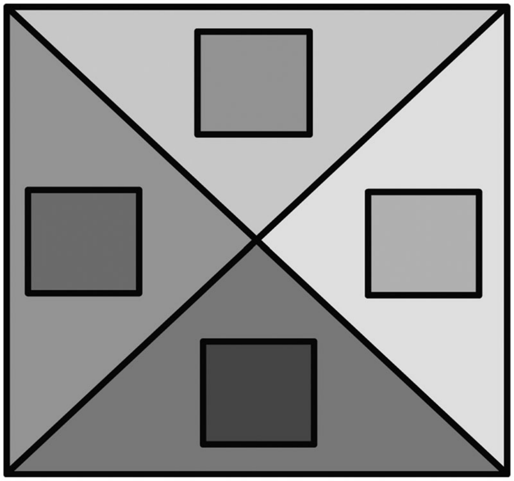

Figure 3. The AOIs (areas of interest) used for calculating the percentage of correct anticipations. Each triangle was considered the AOI for the square that was positioned inside of it.

Learning. Mixed-design ANOVA (2×6) was used to analyse the effect of group as above and the within-subjects factor of learning (Blocks 1–6). Main effect for group did not reach significance, $F(1, 57) = 0.78$, $p = .38$, ES = 0.01. Learning main effect was significant, $F(5, 285) = 23.7$, $p < .01$, ES = 0.29. The group by learning interaction did not reach significance, $F(5, 385) = 0.5$, $p = .77$, ES = 0.01. These results suggest that both groups showed an equal increase in the percentage of correct anticipations over the six learning blocks.

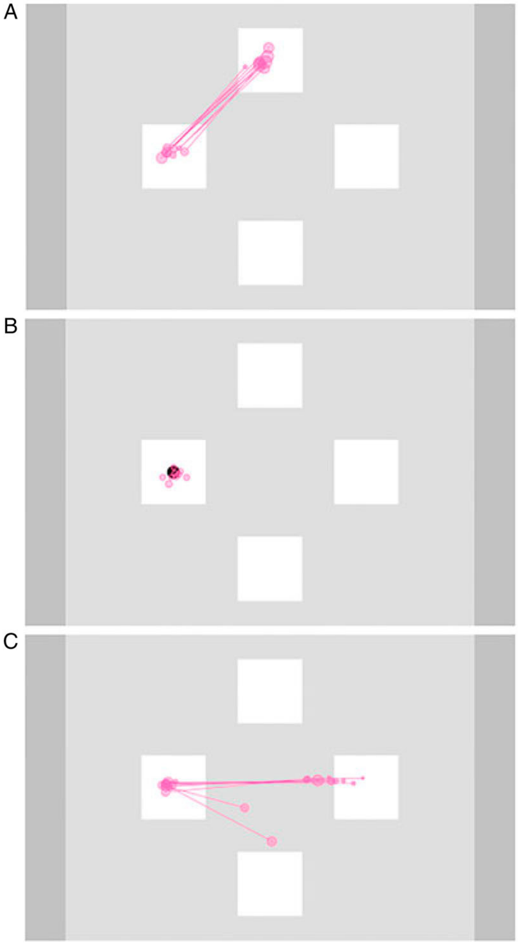

Figure 4. One participant's saccadic eye movements while performing the task in Block 6. (A) A blank slide following a slide in which the target was located in the upper square. Saccadic eye movement is from the top square to the left square. (B) A target slide. There is no saccadic movement because the eyes had already shifted to the left square before the target appeared. (C) A blank slide. Most of the saccadic movement is from the left square to the right square where the next target is expected to appear. To view this figure in colour, please visit the online version of this Journal.

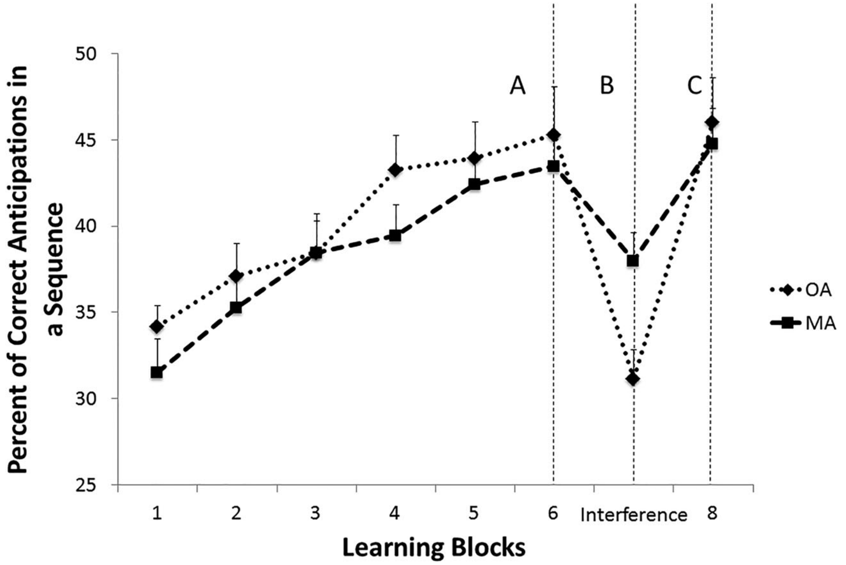

Figure 5. The mean percentage (and *SE*) of anticipations during a sequence (12 trials) in each of the eight blocks of the serial reaction time (SRT) task, for both the manual activated (MA) and ocular activated (OA) groups. The seventh block is an Interference block and contains the alternative sequence.

Interference. Mixed-design ANOVA (2 × 2) was used to explore the effect of group as above and the within-subjects factor of interference (Block 6 vs. Block 7). The group main effect did not reach significance, *F* (1, 57) = 1.07, *p* = .3, ES = 0.02. The interference main effect did reach significance, *F*(1, 57) = 40.47, *p* < .01, ES = 0.41. The group by interference interaction reached significance as well, *F*(1, 57) = 7.85, *p* < .01, ES = 0.12. As can be seen in Figure 5, the cost of transference was more pronounced for the OA than for the MA group.

Recovery from interference. Mixed-design ANOVA (2 × 2) was used to explore the effect of group as above and the within-subjects factor of recovery from interference (Block 7 vs. Block 8). Group main effect did not reach significance, *F*(1, 57) = 1.35, *p* = .25, ES = 0.02, but recovery from interference did reach significance, *F*(1, 57) = 53.05, *p* < .01, ES = 0.11. The Group × Recovery from Interference interaction reached significance as well, *F*(1, 57) = 7.33, *p* < .01, ES = 0.11. As can be seen in Figure 5, the recovery rate of the OA group was steeper than that of the MA group.

Comparison of baseline with interference. Mixed-design ANOVA (2 × 2) was used to explore the effect of group as above and the within-subjects factor of interference (Block 1 vs. Block 7). Group main effect did not reach significance, *F*(1, 57) = 1.57, *p* = .22, ES = 0.03. The difference between the baseline (Block 1) and the interfering block (Block 7) did not reach significance either, *F*(1, 57) = 1.23, *p* = .27, ES = 0.02. These findings should be interpreted cautiously because of the significant group by interference interaction, *F*(1, 57) = 9.29, *p* < .01, ES = 0.14. As can be seen in Figure 5, while percentage of correct anticipations in the interference block went back to baseline in the OA group, performance at the interference block in the MA group remained significantly better than baseline.

Explicit learning and generate task

We used an independent *t* test to compare the explicit learning score (the sum of scores from the first two questions—maximum 2 points) and the generate task scores (number of elements reproduced from the sequence—maximum 12 points) between the two groups. The average explicit learning score of the OA group (*M* = 0.73, *SD* = 0.88) did not significantly differ from that of the MA group (*M* = 0.85, *SD* = 0.76), *t*(40) = 0.48, *p* = .60. Similarly, the average generate task score of the OA group (*M* = 5.08, *SD* = 1.92) did not significantly differ from that of the MA group (*M* = 5.78, *SD* = 1.47), *t*(44) = 1.35, *p* = .19. Furthermore, performance was significantly above chance, $t(45) = 5.33$, $p < .01$.

In order to evaluate the correlations between the explicit learning and generate task measures and the implicit learning measures, we calculated two learning measures (RT and anticipation) and two interference measures (RT and anticipation). Learning was measured by the difference in performance between the sixth and the first block. Because lower RT reflects better performance while higher anticipation rates reflect better learning, learning was calculated differently in order to generate positive scores to reflect better learning. Therefore for the RT measure, learning was calculated as 1st – 6th block, and for anticipation, learning was calculated as 6th – 1st block. The same was done for interference, in which the RT measure was calculated as 7th – 6th block, and interference for anticipation was calculated as 6th – 7th block. Thus for all measures, higher scores reflect better learning.

We conducted bivariate Pearson product moment correlations between the learning and interference measures and between the explicit and generate scores, for each group separately. As shown in Table 1, in the MA group, none of the correlations between the implicit RT and anticipation learning measures and the explicit and generate measures reached significance. As can be seen in Table 2, in the OA group, implicit learning and interference RT measures as well as the implicit anticipation measure were significantly correlated with the generate measure. However, the explicit score correlated significantly only with the implicit anticipation scores. Overall, this indicates that higher explicit knowledge was associated with better sequence learning for the OA group only, and not for the MA group.

General discussion

The key advantages of this study are that it enables direct comparisons between oculomotor and manual sequence learning, as well as direct measurements of anticipation for these two forms of sequence learning by tracking eye movements. Consistent with previous studies (Albouy et al., 2006; Kinder et al., 2008; Marcus et al., 2006) sequence learning was evident in the OA version of the SRT. By comparing the OA and MA versions of SRT we were able to demonstrate that the extent of sequence learning in these two versions of the task was identical. As reported in the procedure section, extra time was needed between blocks in the OA version to enable calibration before each block, which is critical for this task. As noted in the Method section, the precision of the eye movement calibration in the MA task was constantly monitored, and the experiment was stopped if a deviation was detected. Judging by the results there is no reason to believe that this minor methodological change affected the results in any way.

Nevertheless, there is a possibility that the slight methodological differences between the tasks made the OA version more susceptible to explicit strategies than the MA version, perhaps by allowing more consolidation time between blocks, or more time to think about an explicit strategy. This interpretation might explain the interesting dissociation in the correlations with explicit learning, indicating that the OA group showed more explicit knowledge about the sequence than the MA group.

These results have very important theoretical implications. As explained above, Kinder et al. (2008) describes S–R mappings as being necessary in order for sequence learning to occur in the SRT. Thus from this point of view, the sequence learning that was

Table 1. Pearson product–moment correlations between implicit and explicit measures of sequence learning in the MA group

	Learning RT	Interference RT	Learning anticipation	Interference anticipation
Explicit score	.106	.390	−.039	.251
Generate score	.205	.328	.211	.021

Note: MA = manual activated; RT = reaction time.

Table 2. Pearson product–moment correlations between implicit and explicit measures of sequence learning in the OA group

	Learning RT	Interference RT	Learning anticipation	Interference anticipation
Explicit score	.060	.305	.398*	.480*
Generate score	.584**	.534**	.430*	.380

Note: OA = ocular activated; RT = reaction time.
*$p < .05$. **$p < .01$.

demonstrated in the OA version of the SRT task in which S–R pairing is automatic argues against the S–R theory. However, the alternative interpretation of the S–R theory claims that a *sequence* of S–R mappings is learned in the SRT task (Deroost & Soetens, 2006; Willingham et al., 1989). Thus, the fact that S–R pairing is automatic does not prevent the *sequence* of these S–R pairs from being learned.

An important practical implication of these findings is that the OA version of the SRT can replace the MA version of the test and make it possible to test populations with motor deficits such as quadriplegics, or patients with Parkinson's disease who struggle with manual responses.

Although sequence learning was evident in both the MA and OA versions of the SRT, there are still several informative differences. One is that while RT in the interference block went back to baseline in the OA group, in the MA group, performance in the interference block was still significantly better than baseline. These results are consistent with previous studies that used the standard MA version of the SRT and found that RT in the interference block does not return to baseline level. The common interpretation of these results is that the reduced RT across the learning blocks reflects general aspects of the task such as S–R mapping, in addition to pure sequence-learning (Helmuth et al., 2000). Thus, this aspect of learning is preserved even when the sequence has been changed. This is supported by the present study in which RT in the MA group did not return all the way to baseline level because certain aspects of learning are shared regardless of the specific sequence. However, the fact that RT in the OA group did go back to baseline level indicates that it is a pure measure of sequence learning and does not include S–R mapping. As claimed by Kinder et al. (2008), the S–R (stimulus presentation and oculomotor response) association in the OA version of SRT is automatic and exists prior to training, unlike in the MA version. Furthermore, a close look at Figure 2 reveals two interesting findings. First is that in the MA group, RTs in the transfer block are very similar to those of Block 2. Second, RT slopes were similar for the two groups from Blocks 3 to 6. Therefore, it would be reasonable to assume that in the MA version, S–R mapping is achieved by the end of the first two blocks, and from that point on, decreasing RT reflects pure sequence learning as in the OA version.

Reduced RT in sequence learning is considered an indirect indication of improved anticipation of the next target position, as a function of training (Dale et al., 2012). The paradigm used in this study enabled us to measure anticipation directly by recording eye movements. Shifting the eyes towards the next position prior to the appearance of the next stimulus was interpreted as correct anticipation. The results clearly show an increase in the percentage of correct anticipations as a function of training. Furthermore, when a new sequence was presented, the percentage of correct anticipations significantly decreased. The learning pattern reflected by the percentage of correct anticipations (Figure 5) mirrors the pattern reflected by RT (Figure 2). It is interesting to note that the increased percentage of correct anticipation as a function of training was identical in the MA and OA versions of the task. However, the decline in the percentage of correct anticipations in the interference block was steeper in the OA than in the MA group. As suggested above, the steeper decline in the percentage of correct anticipations could be interpreted as an indication that OA is a purer measure of sequence learning than MA, which does not include S–R mapping. It was found that explicit awareness measures correlate with implicit learning and anticipatory measures only for the OA group. Thus, an alternative interpretation could be that a more precipitous decline in anticipation was shown for the OA than for the MA groups on the transfer block due to explicit knowledge.

Although no differences were shown in the amount of anticipation or explicit learning between groups, the correlation between the implicit learning and anticipation measures and the explicit learning scores reached significance in the OA version only. This may indicate that during OA learning of the SRT, awareness of the existence of a sequence might influence anticipation. This is consistent with Dale et al. (2012) who discovered an association between awareness of the sequence and the tendency to move the mouse towards the next predicted position.

In summary, this study has demonstrated that sequence learning can be accomplished using OA. Furthermore, these results suggest that even when S–R mapping is automatic, sequence learning does occur in the SRT task. In addition, there are several indications that this form of learning is a purer measure of sequence learning than the standard MA version. Furthermore, unlike the standard MA versions of the SRT that inferred anticipation from the decline in RT, the paradigm used in this study enabled us to measure anticipation directly using eye tracking.

Using the OA version of the SRT to study sequence learning has significant methodological as well as theoretical implications. This version of the task makes sequence learning tests possible with populations that struggle to respond manually because of hemiplegia or Parkinson's disease, and with populations with known slower RTs such as children and elderly individuals. Furthermore, as shown above, the sequence learning measures extracted from the OA version of the SRT are purer than those extracted from the standard MA version of the task.

The fact that anticipation was measured directly using this paradigm has important theoretical potential, as it allows researchers to track the gradual build-up of sequence learning. This paradigm makes it possible to measure which components of the sequence were anticipated consistently as a function of training, and whether the entire sequence (i.e., all of its locations) or only part of it was learned. This will enable comparisons between groups that are not only based on RT improvement rates but also on the number of components in the sequence that were learned at the different stages of the learning process.

Disclosure statement

No potential conflict of interest was reported by the authors.

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