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Annette Kinder ^a; Martin Rolfs ^a; Reinhold Kliegl ^a
^a University of Potsdam, Potsdam, Germany

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Short article

Sequence learning at optimal stimulus–response mapping: Evidence from a serial reaction time task

Annette Kinder, Martin Rolfs, and Reinhold Kliegl

University of Potsdam, Potsdam, Germany

We propose a new version of the serial reaction time (SRT) task in which participants merely looked at the target instead of responding manually. As response locations were identical to target locations, stimulus–response compatibility was maximal in this task. We demonstrated that saccadic response times decreased during training and increased again when a new sequence was presented. It is unlikely that this effect was caused by stimulus–response (S–R) learning because bonds between (visual) stimuli and (oculomotor) responses were already well established before the experiment started. Thus, the finding shows that the building of S–R bonds is not essential for learning in the SRT task.

Numerous studies have explored the learning of structured sequences under incidental learning conditions. The prototypical task to study this type of learning is the serial reaction time (SRT) task. In the original version of this task, participants press as quickly as possible four keys that correspond to four target locations on a computer screen (Nissen & Bullemer, 1987; Willingham, Nissen, & Bullemer, 1989). Unbeknownst to participants, target locations follow a particular sequence that is repeated over and over again. Typically, response times decrease gradually in the course of the experiment. The basic sequence-learning effect is that response times increase again if the sequence changes or is replaced by a random sequence. The research on sequence learning has long been concerned with the question of to what extent knowledge acquired

in this task is implicit (e.g., Wilkinson & Shanks, 2004). Generally, it seems to be difficult to answer this question, mainly because of various methodological problems when measuring explicit versus implicit knowledge (see Buchner & Wippich, 2000; Kinder & Shanks, 2001, 2003; Shanks & St. John, 1994). Another question of constant debate has been what kind of knowledge is acquired in the SRT task and how that knowledge is represented. In the current study we focus on this question rather than on the implicitness/explicitness debate.

The first account of learning in the SRT task was that a sequence of stimulus–response bonds gets represented during training (Willingham et al., 1989). Recently, two studies strengthened this account by showing that stimulus–response compatibility has an impact on sequence learning.

Correspondence should be addressed to Annette Kinder, Department of Psychology, University of Potsdam, PO Box 60 15 53, 14451 Potsdam, Germany. E-mail: kinder@rz.uni-potsdam.de

Koch and Hoffmann (2000) used compatible and incompatible stimulus–response mappings in order to manipulate the structure of a stimulus sequence and a response sequence independently of each other. In one experiment, they found that the incompatible stimulus–response mapping had a positive effect on learning a response sequence. It is difficult to interpret this finding, however, because another experimental factor (identical or different structure of response and stimulus sequence) was confounded with stimulus–response compatibility. In a recent study by Deroost and Soetens (2006), stimulus–response compatibility was addressed more directly and was manipulated systematically: Either stimuli and response keys were in the same order (compatible) or the order was reversed (incompatible). In accord with an S–R account the authors found that the sequence learning effect was significantly greater when stimulus–response compatibility was low.

In this study we asked whether the building of S–R bonds is essential for sequence learning in the SRT task. To answer this question we used a highly automatic response: a saccadic eye movement to a peripheral target rather than a manual response. As response locations were identical to target locations, S–R compatibility was maximal in this task. Most important, associations between Ss (the visual stimuli) and Rs (the oculomotor responses) were already very well established before training began. In this situation it is unlikely that stimulus–response bonds are subject to learning as assumed by Willingham et al. (1989). Rather, learning in this paradigm probably would be based on either a speed-up in spatial orientations and/or oculomotor responses.

Two recent studies measured eye movements in the serial reaction time task. Marcus, Karatekin, and Markiewicz (2006) recorded eye movements during an observational and a manual version of the SRT task and found more correct anticipatory eye movements to the next target location with a regular sequence than with a random sequence. They hypothesized that these responses are manifestations of shifts of visuospatial attention to likely stimulus locations. Albouy et al. (2006)

investigated saccadic response times in a variant of the SRT task in which participants had to fixate the target in order to detect the target changing its colour for a very short period of time (which happened in 20% of the trials). In contrast to the classical SRT task, stimuli were presented at a constant rate and were not triggered by the response. Nevertheless Albouy et al. found that saccadic response times showed the typical sequence–learning pattern: They decreased during training and increased again when the training sequence was changed in a random sequence. In this study, we developed a new variant of the SRT, which we tried to model even more closely to the classical Nissen and Bullemer (1987) paradigm than Albouy et al. did. In our study, stimuli were not presented at a constant rate but the next stimulus presentation was always triggered by the participant's (saccadic) response.

Method

Participants

A total of 15 university students participated in the experiment in partial fulfilment of study requirements. The data of 3 additional participants were excluded because of calibration problems or because they had participated in another sequence–learning experiment before.

Apparatus

Participants were seated in a silent and darkened room with the head positioned on a chin rest, 50 cm in front of a computer screen. Stimuli were presented on a 22-inch iiyama HM204DT CRT (1,024 by 768 resolution; refresh rate 100 Hz). The experiment was controlled by an Apple Power Macintosh G4 computer. Eye position data were recorded and available on-line using an EyeLink-II system (SR Research, Osgoode, ON, Canada) with a sampling rate of 500 Hz and a noise-limited spatial resolution better than 0.01° . The experimental software controlling stimulus display and response collection was implemented in Matlab (MathWorks, Natick, Massachusetts, USA), using the Psychophysics (Brainard, 1997;

Pelli, 1997) and EyeLink (Cornelissen, Peters, & Palmer, 2002) toolboxes.

Stimuli

The target was a black dot subtending a visual angle of 0.5° that appeared in the centre of one of four white squares (visual angle: 2°) on a grey screen background. The four squares were placed 5° left, right, below, and above the screen centre forming a diamond (see Figure 1). Target locations are denoted by the numbers from 1 to 4 (clockwise) starting from the utmost left target.

Procedure

SRT task. Participants were instructed to look as quickly as possible at the black dot that would appear in one of the four squares on the screen and to make as few mistakes as possible. No mention was made that stimuli would appear in a repeating sequence.

After participants had been instructed they were calibrated with a standard 9-point grid for both eyes. Calibration was repeated after each block of trials. In addition, the experimenter carried out a calibration when the tracker did not detect an eye movement into one of four regions defined by the experimenter (see below) within 2,500 ms from target onset.

A total of 8 participants were trained on Sequence 1 (3 4 2 3 1 2 1 4 3 2 4 1) and 7 participants on Sequence 2 (3 4 1 2 4 3 1 4 2 1 3 2). Sequences were adopted from Wilkinson and Shanks (2004) and are equated with respect to location frequency (each location occurs three times) and first-order transition frequency (each location is preceded once by each other location) and do not contain repetitions. Both contained one reversal (Sequence 1: 1 2 1; Sequence 2: 3 2 3). The only difference between the sequences is in their second- and higher order transition probabilities. For participants trained on Sequence 1, the test sequence in Block 13 was Sequence 2 and vice versa.

Before the first block started, participants were presented with a single training sequence consisting of 12 target locations in order to make sure that they had understood the instructions. Thereafter, they were presented with the training sequence for 12 blocks of 100 trials, then received the test sequence for another 100 trials in Block 13, and finally, in Blocks 14 and 15, were presented with the training sequence again. Each block began with a random target location, and thereafter targets appeared according to the sequence corresponding to the block type (training or test) and the sequence condition (Sequence 1 or 2 being the training sequence, see Wilkinson & Shanks, 2004).

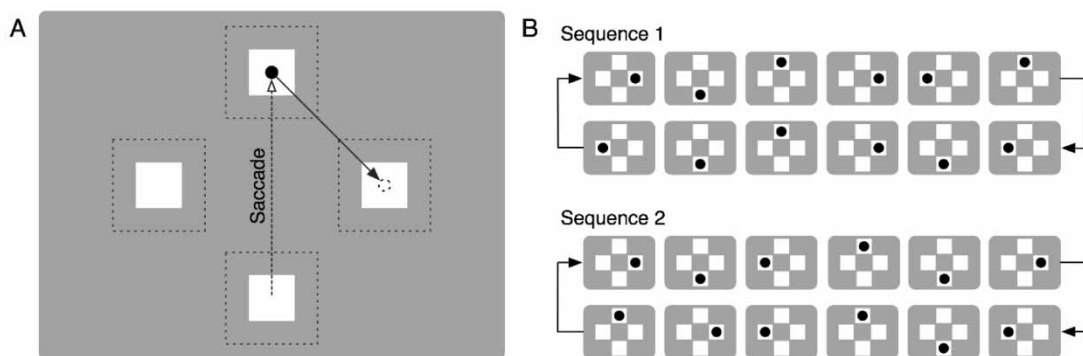


Figure 1. Illustration of the experimental display. (A) Exemplary trial of a sequence. One of the four white target regions contained a saccade target (black dot). When the eyes had crossed the invisible border to the target (dashed squares) for 90 ms, the dot disappeared and reappeared subsequently at the next location in the sequence (dashed circle). (B) Spatial sequences used in the experiment. Participants were trained in one sequence for 12 blocks of 100 trials and then tested in the other sequence in a test block of 100 trials. In 2 final blocks, the trained sequence was presented again.

Four quadratic regions were defined whose centres were identical to the centres of the white squares presented on the screen. Their side length subtended a visual angle of 4° and thus was twice as large as the side length of the white squares. A period of 90 ms after the tracker had detected that the eyes had moved into the target region, a new trial started. An eye movement into a region not corresponding to the target location was signalled to participants by an error tone. After making a mistake, participants had to move their eyes into the correct region in order to start the next trial.

The time that elapsed from target onset until the gaze had moved into the region corresponding to the target was recorded as saccadic response time, equivalent to the response time in the manual version of the serial reaction time task. Only latencies of correct responses were recorded. Responses that occurred before the target appeared (anticipatory responses) were also excluded from the analysis.

Recognition test. After the eye movement task participants performed a paper-and-pencil recognition test, which contained parts of the training sequence, the transfer sequence, and a new sequence that had not occurred in the SRT task. The new sequence was identical to the two other sequences with respect to frequency of target locations, frequency of first-order transitions, and absence of repetitions. The recognition test contained 18 four-element partial sequences: 6 of each sequence (training, transfer, and new). Stimuli forming a four-element partial sequence were arranged from left to right in a line. For each partial sequence, participants judged on a 6-point rating scale ranging from “never” to “very often” how often this sequence had occurred in the training scale.

Results

The type of training and test sequence did not affect saccadic response times or errors, and thus the data were collapsed across sequence types in the following analyses. The level of significance

was set to .05. Greenhouse–Geisser adjustments were performed where appropriate.

Saccadic response times

As can be seen in Figure 2 (top panel), saccadic response times decreased from Block 1 to Block 12. In Block 13, where the new sequence was presented, saccadic response times increased in both groups and decreased again in Block 14 when the training sequence was resumed. To test this effect statistically, we computed the mean saccadic response time in Blocks 12 and 14 and tested it against the saccadic response time in Block 13. A t test revealed that the saccadic response times were significantly longer in Block 13 than in the two adjacent blocks, $t(14) = 3.1$. Response times in the 13th block did not differ from response times in the first block of trials, $t(14) = 1.50$.

Errors in saccadic responses

Figure 2 (bottom panel) shows the mean number of errors across blocks of trials. As can be seen, the number of errors was low and did not increase in the 13th block. Accordingly, a t test revealed no significant difference between errors in the 13th block and mean errors in the 12th and 14th blocks, $t(14) = 0.07$.

Discussion

In the present study we designed a new variant of the SRT task, in which participants had to look at the target rather than responding to it manually. We found that saccadic response times exhibited the typical pattern normally seen in manual response times: Saccadic response times decreased in the course of training and increased again when a new sequence was introduced. Our findings yielded direct evidence of sequence learning in a situation where no manual responses had to be executed. It was also shown that sequence learning is possible in a highly automated response, when all other important factors (such as the fact that the response triggers the next stimulus presentation) are identical to the classical SRT task. The very same type of learning could occur in the observational version of the SRT task, in

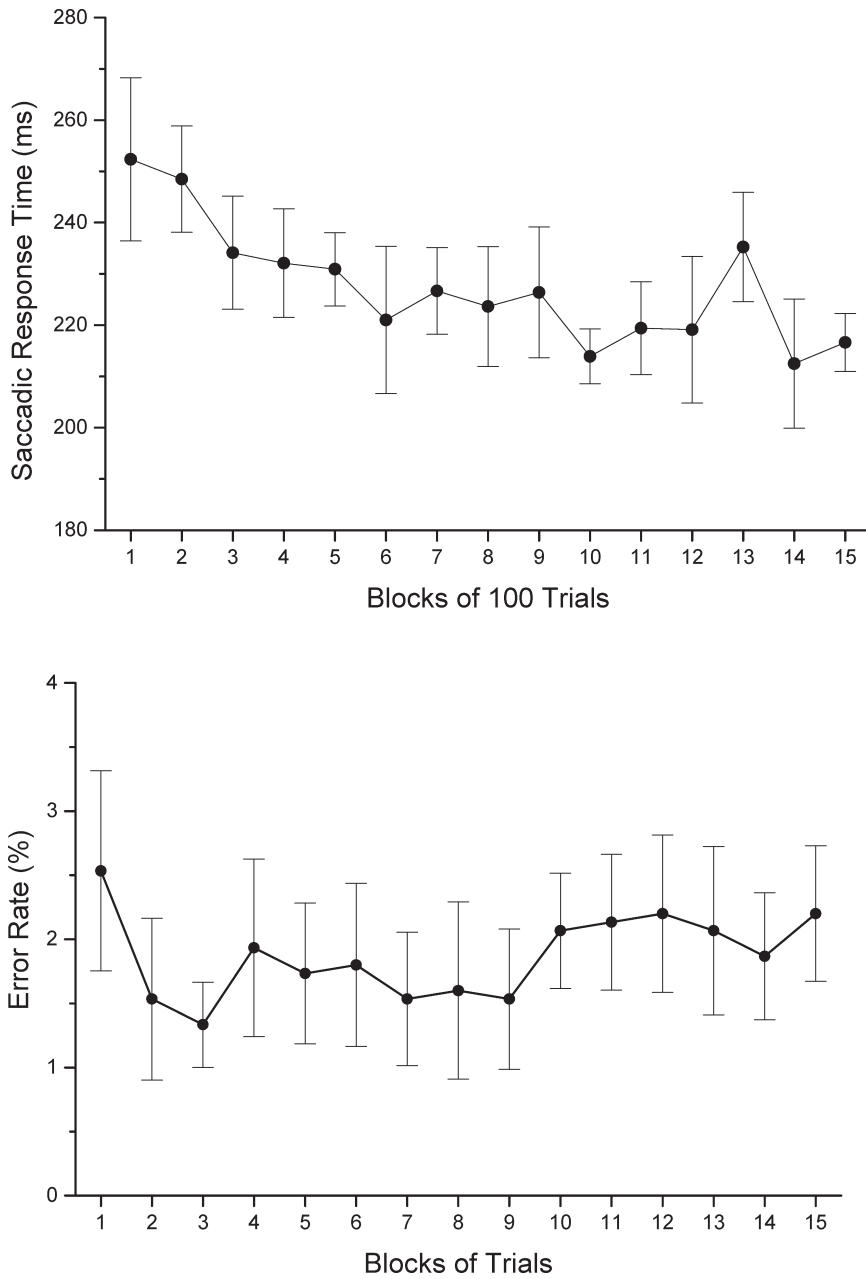


Figure 2. *Top: Saccadic response times. The test sequence was introduced in Block 13. In Blocks 14 and 15 the training sequence was resumed. Error bars indicate 95% within-subjects confidence intervals (Loftus & Masson, 1994). Bottom: Mean errors. The test sequence was introduced in Block 13. In Blocks 14 and 15 the training sequence was resumed. Error bars indicate 95% within-subjects confidence intervals (Loftus & Masson, 1994).*

which sequence learning takes place when participants merely are looking at the stimuli (e.g., Bird, Osman, Saggerson, & Heyes, 2005; Howard, Mutter, & Howard, 1992). Thus, our findings provide a possible explanation of learning effects found in this kind of task.

As noted before, it is unlikely that learning in our paradigm is due to learning a sequence of stimulus–response bonds as suggested by Willingham et al. (1989), because associations between stimuli and responses were already extremely strong before training begins. It is more likely that participants learned a sequence of responses or a sequence of target locations. One possible way of response–response learning is referred to as effector-specific learning. In our paradigm, this would mean that a sequence of oculomotor movements is learned. However, as no evidence for effector-specific learning was found in manual responses (see Cohen, Ivry, & Keele, 1990; Keele, Jennings, Jones, Caulton, & Cohen, 1995), it is implausible that such learning takes place in saccadic responses. In contrast to effector-specific learning, there is clear evidence for both learning of target locations and learning of response locations in the SRT literature (e.g., Mayr, 1996; Remillard, 2003; Willingham, Wells, Farrell, & Stemwedel, 2000). In the classical SRT paradigm, target locations are placed on the screen, and response locations are defined by the response keys. In our paradigm, however, both are placed on the screen, or, in other words, the response locations *are* the target locations, and vice versa. As a result, there is only one type of learning, which can be referred to as perceptual or attentional learning.

The tight control afforded by gaze-contingent display of saccade targets, however, does not rule out effector-specific learning. In other words, we cannot conclude that learning in our paradigm is “purely” perceptual. It is possible that attentional and oculomotor factors in sequence learning closely depend on each other. According to the premotor theory of attention (Rizzolatti, Riggio, Dascola, & Umiltà, 1987), indeed shifts of attention are the result of programming a saccade. Thus, learning a sequence of attention shifts could be considered a by-product of learning a

sequence of eye movements. Further research is needed to clarify the interactions of attention and oculomotor processes in sequence learning.

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