The Simon effect in a discrete sequence production task: Key-specific stimuli cannot be ignored due to attentional capture[☆]

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ABSTRACT

Two experiments examined whether practicing discrete key pressing sequences eventually leads to a disregard of the key-specific stimuli, as suggested by sequence learning models, or whether these stimuli continue to be relied upon because the associated luminance increase attracts visuospatial attention. Participants practiced two sequences by reacting to two fixed series of seven letter stimuli, each displayed at a location that did or did not correspond with the required response location. Stimulus use was indicated by a Simon effect in that key presses were slowed when stimulus and key locations did not correspond. Experiment 1 demonstrated that letter stimuli continued to be used as the Simon effect occurred with each sequence element, and this remained quite stable across practice and did not differ for familiar and unfamiliar sequences. Experiment 2 showed that the Simon effect remained present even with meaningless stimuli that were often even harmful. These findings suggest that even in motor sequences that can be executed without element-specific stimuli attention attraction enforces stimulus use. The data further supported the assumptions that S-R translation and sequencing systems are racing to trigger individual responses, and that explicit sequence representations include spatial and verbal knowledge.

1. Introduction

The change in serial movement skill over practice and time has been studied extensively over the last half-century (for reviews, see e.g., Abrahamse, Jiménez, Verwey, & Clegg, 2010; Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013; Adams, 1971; Doyon et al., 2009; Lashley, 1951; Perruchet & Pacton, 2006; Rhodes, Bullock, Verwey, Averbeck, & Page, 2004; Rosenbaum, 2010; Schmidt, 1975; Verwey, Shea, & Wright, 2015; Wright et al., 2016). The study of motor sequencing skills in the laboratory usually involves tasks consisting of series of aimed movements in the flexion–extension (FE) task (Panzer, Wilde, & Shea, 2006; Shea, Panzer, & Kennedy, 2016), and sequential key pressing tasks like

the serial reaction time (RT) task (Nissen & Bullemer, 1987), the NxM task (Hikosaka, Rand, Miyachi, & Miyashita, 1995; Rand, Hikosaka, Miyachi, Lu, & Miyashita, 1998), and the presently used *discrete sequence production* (DSP) task (Verwey, 1999; for a review, see Abrahamse et al., 2013).[1]

Discrete motor sequences are often trained by responding to fixed series of element-specific stimuli. With practice, representations develop that according to models of motor sequence learning eliminate the need for element-specific stimuli (Abrahamse et al., 2013; Verwey et al., 2015). However, visual search studies show that the luminance change that accompanies stimulus display automatically captures visuospatial attention (e.g., Belopolsky, Schreij, & Theeuwes, 2010;

[1] As people do not always realize the differences between the DSP task and the serial RT task (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Nissen & Bullemer, 1987), we would like to emphasize the main differences. Most importantly, the serial RT task involves cycling through a single key pressing sequence so that successive key presses are usually not prepared as a unit. Also, sequence execution rate is limited in the serial RT task because each stimulus is preceded by a 100 to 250 ms response-stimulus interval. Furthermore, practice in the DSP task usually involves more trials. As a result, skill in the serial RT task continues to involve reactions to stimuli that benefit from associative priming (Abrahamse et al., 2010) while in the DSP task sequencing skill is attributed to various sequence representations that can be prepared and that allow DSP sequences to be executed without key-specific stimuli.

Jonides & Yantis, 1988; Theeuwes, 2010; Yantis & Jonides, 1984). This may imply that, in contrast to the claim of motor sequence learning models, the contribution of key-specific stimuli in sequencing tasks will never reduce, no matter the amount of practice. The present study therefore examined whether learning sequential motor skills by responding to key-specific stimuli in the DSP task involves a reducing reliance on these stimuli, or whether these stimuli continue to be used because key-specific stimuli capture visuospatial attention.

1.1. Skill in discrete keying sequences

A typical DSP task initially consists of key presses given in response to two fixed series of 6 or 7 key-specific stimuli. In this task sequence control is explored using the RTs of the resulting series of key presses. Results of various DSP task studies indicate that while repeatedly reacting to these key-specific stimuli participants develop knowledge of the sequences in terms of verbal, spatial and/or motor representations (Abrahamse et al., 2013; Verwey et al., 2015). According to the Cognitive framework for Sequential Motor Behavior (C-SMB) these distinct knowledge representations develop at different rates (Verwey et al., 2015). They also differ in the amount of central-cognitive processing required for triggering the individual responses. While during the first tens of practice trials spatial and verbal sequence representations develop that require substantial cognitive processing to extract the individual responses, during the ensuing hundreds of practice trials motor chunk representations develop that require cognitive processes only for selecting and initiating motor sequences. Consequently, practice is characterized by control shifting from slower to faster cognitive systems and reduced involvement of higher levels of cognition. This notion is consistent with the shifts in neural activity observed in various studies during practice (Ashby, Ennis, & Spiering, 2007; De Kleine & Van der Lubbe, 2011; Hélie, Ell, & Ashby, 2015; Karni et al., 1998). Importantly, the distinction between various functional systems that the C-SMB model proposes suggests hypotheses as to the involvement of various neural networks. Some of these hypotheses were tested and confirmed in a recent fMRI study (Verwey, Jouen, Dominey, & Ventre-Dominey, 2019).

C-SMB postulates that execution of motor sequences involves a race between cognitive systems to trigger each next movement in the sequence. This race assumption seems an important principle of cognition as it emerges in many task domains (e.g., Hughes, Fulham, & Michie, 2016; Kornblum, Hasbroucq, & Osman, 1990; Logan, 1988; Raab, 1962; Selfridge, 1959; Ulrich & Miller, 1997). A race between cognitive systems implies that even a generally slower system increases execution rate as long as its processing time distribution overlaps with that of faster systems (Abrahamse et al., 2013; Verwey, 2003; Verwey et al., 2015). The race assumption explains, for example, that even in highly practiced sequences that can be executed without visual stimuli sequence execution rate stills suffers when these stimuli are no longer displayed (Ruitenberg, Verwey, Schutter, & Abrahamse, 2014; Verwey, 1999; Verwey, Abrahamse, Ruitenberg, Jiménez, & De Kleine, 2011). Nevertheless, it is possible that eventually sequencing systems become so fast that the S-R translation system always loses the race (i.e., the processing time distributions no longer overlap). Also, participants may in the course of practice stop processing key-specific stimuli, for example, because they see no benefit in attending to them because they have full explicit knowledge of the sequence (Experiment 2 in Verwey, in press). However, the latter study involved key-specific stimuli consisting of color changes that did not attract visuospatial attention because they had the same luminance as the background. The question remains whether participants may also be able to stop processing key-specific stimuli when these stimuli do involve luminance changes.

1.2. The Simon effect

It is well-known that a response to a stimulus presented at a location that does not correspond with that of the response is slower than when that stimulus is presented at a spatially corresponding location. This was first observed by Richard Simon (1969; Simon & Rudell, 1967) and was later referred to as the *Simon effect* (Hedge & Marsh, 1975). The effect was defined as "a 'natural' tendency to react towards the source of stimulation" (p174, Simon, 1969). According to Lu and Proctor (1995) the Simon effect is probably caused by response slowing when the stimulus is displayed at a non-corresponding location rather than by a speed up when the stimulus is displayed at the corresponding location. The Simon effect is a short-lived phenomenon that in choice RT tasks disappears with RTs over about 500 ms (e.g., De Jong, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995; Simon, Acosta, Mewaldt, & Speidel, 1976). Still, it does not reduce much with extensive practice (Logan, 2003; Prinz, Aschersleben, Hommel, & Vogt, 1995; Proctor & Lu, 1999; Simon, Craft, & Webster, 1973).

That responding is affected by the correspondence between stimulus and response locations suggests involvement of a shared system for perception and action. According to a modified version of the premotor theory of attention (Rizzolatti, Riggio, Dascola, & Umiltá, 1987) there is a supramodal spatial representation that links perceptual and motor space (Van der Lubbe, Abrahamse, & De Kleine, 2012). This representation is most likely based in the parietal lobe (Andersen & Buneo, 2002). Abrahamse and Van der Lubbe (2008) argued that it is the directing of spatial attention that induces the Simon effect as stimuli presented at already attended locations showed a reduced or no Simon effect. This suggests that the Simon effect is caused by stimulus display automatically attracting spatial attention (e.g., Rubichi, Nicoletti, Iani, & Umiltá, 1997; van der Lubbe, Keuss, & Stoffels, 1996).

Only few studies have explored the Simon effect in the context of a sequential keying task. Logan (2003) explored the Simon effect when expert typists typed 3-, 4- and 5-letter English words in response to display of these words left and right of a central fixation symbol. As predicted, the results showed a Simon effect on the first key press caused by the display location of the word. Subsequent key presses did not show this effect, and this was attributed to the word location code decaying quickly after pressing the first key (e.g., Eimer et al., 1995). The apparent short life of spatial codes suggested to us that in the rapidly executed DSP sequences manipulating the location of each key-specific stimulus would induce a Simon effect at each response, and that the Simon effect would therefore indicate whether key-specific stimuli are used.

The Simon effect has been observed in an adjusted version of the serial RT task in which participants cycled through an 8 element series of binary responses (Tubau & López-Moliner, 2004; also see Koch, 2007). Those researchers found that the Simon effect reduced with practice for participants with full sequence awareness while less aware participants showed a lasting Simon effect. This difference was attributed to aware participants ignoring the stimuli. Given that stimulus display in those studies was inherently attention attracting this finding suggests that participants disengaged attention from the stimulus area (Belopolsky et al., 2010; Theeuwes, 2010) only when they possessed full explicit sequence knowledge. Yet, this finding does not necessarily mean that awareness play such a role in the DSP task too. After all, in the DSP task familiar sequences can be executed by most unaware and partially aware participants without key-specific stimuli.

1.3. The present experiments

To test the assumption of sequence learning models that participants eventually ignore key-specific stimuli in familiar DSP sequences, even when these stimuli involve a luminance change (Abrahamse et al., 2013; Verwey et al., 2015), we assessed the effect of practice on the Simon effect when performing the DSP task. To that end, the participants practiced two fixed, 7-element, discrete keying sequences in response to successively displayed stimulus letters rather than to the more
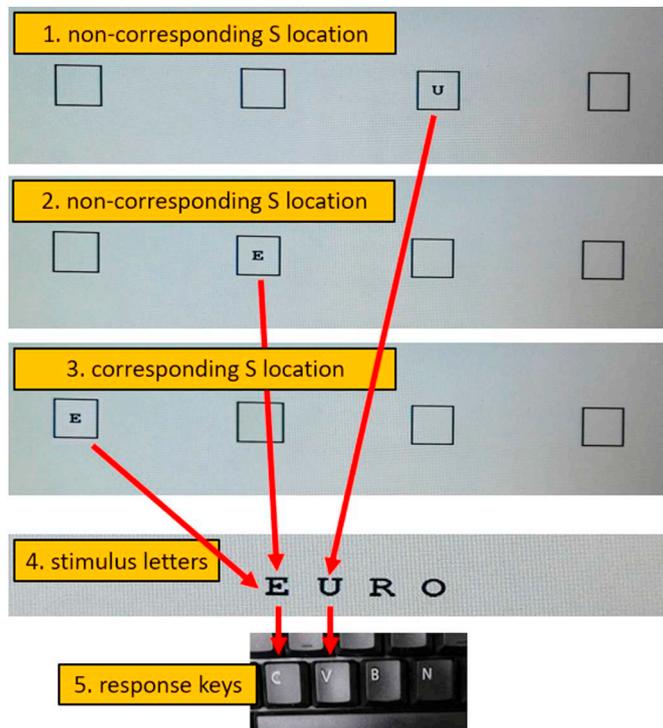
Fig. 1. Stimuli and responses used in Experiments 1 and 2. Successive display of the stimulus letters E U R O in the placeholders (see the above Frames 1 to 3) indicated the order of pressing the C V B N keys in the DSP (discrete sequence production) sequences, respectively. The Simon effect was induced by displaying these letters at locations that corresponded (Frame 3) and that did not correspond (Frames 1 and 2) with the relative locations of the response keys (Frame 5). Frames 4 and 5 together indicate the letter-key mapping that participants learned in Block 1. The letters E U R O in Frame 4 were displayed as an aid in the first half of Block 1.

commonly used stimulus locations.[2] Using letter stimuli as imperative stimuli allowed displaying the key-specific stimuli at locations that did and did not correspond with the location of the required response and induce a Simon effect. We used letters that differed from those on the keys to prevent RTs to also be affected by a direct association between letters and keys (Fig. 1). For example, when assessing the effect of the location of a letter stimulus on pressing the C-key, we did not want this correspondence effect to be affected by the existing association between the C-letter and the C-key. Hence, participants first learned to press keys to unrelated letters.

Given that the Simon effect has been observed before with > 2 alternative responses (e.g., Akçay & Hazeltine, 2007, found the Simon effect with a 4-choice RT task and; Logan, 2003, even with 22 and more alternatives), and the spatial code of the stimulus is short-lived (Simon et al., 1976), we expected a Simon effect for each response at the start of practice. Experiment 1 tested this and, next, whether this effect would reduce with practice and whether it is smaller for familiar than for unfamiliar sequences. Experiment 2 then tested whether processing key-specific stimuli is enforced by attentional capture or is strategic. Experiment 2 further tested the race assumption by assessing whether the Simon effect would be larger for a response that is triggered relatively slowly by the sequencing systems so that S-R translation more often wins the race.

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[2] To prevent confusion, we use the term *location* to denote where in space a stimulus is displayed, and a response is given. We use the term *position* to indicate where in the order of sequence elements (i.e. stimuli and/or responses) an element occurs. So, we talk about *stimulus* and *response locations*, and *sequence positions*.

2. Experiment 1

The *fast-sequencing system hypothesis* assumes that the (central-symbolic and motor chunk) sequencing systems eventually outrun S-R translation. This hypothesis predicts that the Simon effect of non-initial responses reduces and eventually vanishes with practice and is smaller for familiar than for unfamiliar sequences because familiar sequences can eventually be executed without any reliance on key-specific stimuli. Only the first response of familiar sequences should still show the Simon effect because the first stimulus always needs to be identified for sequence selection. Outperforming S-R translation would imply that possible effects of attentional capture would also vanish with practice. This hypothesis is consistent with sequence learning models that suggest that stimuli are eventually ignored (Abrahamse et al., 2013; Verwey et al., 2015).

The *slow-sequencing system hypothesis* posits that even after extended practice S-R translation is not outrun by the sequencing systems. The non-initial responses may show a small reduction of the Simon effect because development of sequencing systems might reduce the contribution of S-R translation, but it should not be much smaller in familiar than in unfamiliar sequences. It should be noted that in choice RT tasks the Simon effect itself also reduces a little with practice but it never vanishes entirely (Logan, 2003; Prinz et al., 1995; Proctor & Lu, 1999; Simon et al., 1973). If such a Simon effect reduction occurs, the Simon effect should reduce with practice for all responses, in familiar and unfamiliar sequences, including the first. This slow-sequencing system hypothesis is consistent with the notion that stimulus display continues to attract visuospatial attention.

In Experiment 1, our prime interest was whether the Simon effect in the second and later responses would be smaller when there are sequence representations to control sequence execution. We therefore assessed whether the Simon effect would reduce across the six practice blocks. In addition, we had participants perform in a test phase in which we explored whether the Simon effect would be smaller in the two *familiar* (i.e., practiced) sequences than in two *unfamiliar* (i.e., novel) sequences. This was done to ensure that a reduction of the Simon effect during practice would be due to sequence familiarity, and not caused by practice reducing the Simon effect itself. We used an awareness test to examine whether a reduction of the Simon effect is related with awareness, just like in the serial RT task (Koch, 2007; Tubau, Hommel, & López-Moliner, 2007; Tubau & López-Moliner, 2004). This test phase also included a condition in which the successive stimulus letters were presented in a single placeholder. Familiar and unfamiliar sequences were executed in this *1-Placeholder condition* to examine whether the Simon effect is caused solely by slowed responding to stimuli at non-corresponding locations, just like in choice RT tasks (Lu & Proctor, 1995).

2.1. Method

2.1.1. Participants

Wühr and Koch (2011) reported that the observed effect size of the Simon effect in their paced serial order response task experiments was large (0.82 on average for Cohen's d). We used GPower's 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009) repeated measures ANOVA design with 1 group and 7 measurements (in a sequence), and used the large effect size of $f = 0.40$ along with other typical parameters ($\alpha = 0.05$, power $1 - \beta = 0.85$) to estimate the proper sample size. This yielded an estimated sample size of 18 for assessing the Simon effect. We rounded this down to 16 in each of the 2 participant groups to facilitate balancing conditions and sequences (see below). Thirty-two students (mean age 22.0 years, 21 females) from the University of Twente, the Saxion University and the Academy of Pop Music and MediaMusic took part in this experiment in exchange for course credit or participant fee (12€). Informed consent was obtained from all participants. The study was approved by the Ethics Committee of the Faculty of Behavior,

Management, and Social Sciences at the University of Twente.

2.1.2. Apparatus

Experiment 1 was programmed and conducted in *E*-Prime 2.0 running under Windows 7. Instructions and stimuli were presented on a 15″ Philips 108 t5 lightframe CRT display at a refresh rate of 75 Hz, with a resolution of 640 × 480 pixels, and 16-bit color depth. Participants used four adjacent keys of a standard QWERTY keyboard, namely C, V, B and N, to react to the stimuli while other keys were disabled. During the experiment, unnecessary programs and Windows 7 services were turned off to ensure accurate RT measurement. The (2.25 m × 2.25 m × 3.50 m) room in which the participant performed the experiment was dimly lit with fluorescent light and was equipped with a video camera for monitoring purposes.

2.1.3. Sequencing task

In Block 1 participants learned the letter-key mappings by responding to individual letter stimuli (i.e., *key-specific stimuli*), presented in a single 12 × 15 mm placeholder displayed at the center of the screen. The stimuli consisted of the letters E, U, R and O, and appeared at the center of the placeholder as a random series of seven letters. Participants placed their left middle (M_L) and index (I_L) fingers on the keys C and V, and their right index (I_R) and middle (M_R) finger on the keys B and N, and were instructed to react to the presentation of the letters by pressing these keys (see Fig. 1). We used letters of a well-known four-letter word to facilitate learning the mapping between stimulus letters and responses. After the last response of a sequence, the display was cleared for 1000 ms, the empty placeholder was shown again for 1000 ms, and then the first letter of the next series was presented. Each ensuing stimulus was presented immediately after onset of the previous key press resulting in a response-stimulus interval (RSI) of 0 ms. Here, and in the other blocks of Experiments 1 and 2, an error was followed by displaying 'Error' in a red and clearly readable font for 2500 ms just above the placeholders. Then, the sequence continued by displaying the next stimulus. During the first 50-trials of practice in Block 1, 'E U R O' was displayed at the bottom of the display to help participants remember the letter-response key mappings. The sequences in Block 1 did not involve a particular stimulus order. Stimuli 1 to 7 are indicated as S_1–S_7, Responses 1 to 7 as R_1–R_7, and RTs associated with S_1–S_7 as T_1–T_7 throughout the remainder of the paper.

Practice Blocks 2 through 6 involved the display of four horizontally aligned 12 × 15 mm placeholders at inter-placeholder distances of 37 mm (see Fig. 1). The letters used as key-specific stimuli were presented at locations that either corresponded or did not correspond with the location of the response keys. As there were four placeholder locations, there was one corresponding as well as three non-corresponding stimulus-response mappings. The likelihood of a stimulus location that corresponded with that of the response was 25% for one half and 37% for the other half of the participants.[3]

A set of four different 7-element sequences was constructed (A: VNBNVBC/$I_LM_RI_RM_RI_LI_RM_L$; B: NVCVNCB/$M_RI_LM_LI_LM_RM_LI_R$; C: BCNCBNV/$I_RM_LM_RM_LI_RM_RI_L$; D: CBVBCVN/$M_LI_RI_LI_RM_LI_LM_R$). In Blocks 2–6 participants practiced two of these sequences while the other two sequences were used as unfamiliar sequences in Block 7. In all blocks, each of the two alternative sequences had a 50% chance of being selected. Participants practiced either sequences A and B, sequences B and

C, sequences C and D, or sequences D and A depending on their assigned participant number. The error message that followed an incorrect key press lasted 2500 ms. This relatively long display time was used to encourage participants to reduce errors. Participants were informed that they would work longer when they made more errors. The program then continued with the next letter of the given sequence.

Block 7 contained four sub-blocks, each involving one of 4 conditions according to a 2 (Familiarity; familiar vs. unfamiliar) × 2 (Placeholder: 1 vs. 4) design. The order of presentation of these sub-blocks was counterbalanced across participants. In the two 1-Placeholder conditions all stimuli were displayed at the same location, but the software continued assigning letters to virtual corresponding and non-corresponding locations to allow analyses with the above design.

2.1.4. Awareness task

We assessed awareness of the two sequences with a computerized awareness task (Verwey & Dronkers, 2019). It involved three different awareness tests that were administered in a counterbalanced order across the participants. In the *Spatial test*, four empty placeholders were displayed in a row in a manner consistent with that used for Blocks 2 through 6. Participants used the mouse to click the placeholders in the same order as the keys had been pressed in each of the practiced keying sequences. Each mouse click was followed by a brief flash of the selected placeholder as response feedback. This test examined explicit knowledge of the locations of the successively pressed keys, that is, explicit spatial sequence knowledge.

In the *Verbal Stimulus test*, the four placeholders were displayed in a rhombus configuration and each placeholder contained a letter. The placeholder at the top contained the letter O, the one at the bottom contained the letter R, and the ones at the left and right contained U and E, respectively. The placeholders were located at a mutual distance of 60 mm and the angles between the connecting lines were 60°. Participants were to click the placeholders in the order of the stimulus letters for each of the two sequences. This test examined explicit verbal knowledge of the order of the stimulus letters.

Finally, in the *Verbal Response test* the four placeholders were displayed in the same rhombus shape as in the Verbal Stimulus test, but this time the placeholders contained the letters of the keys the participants had been pressing. The top and bottom placeholders contained the letters N and B, respectively, and the left and right placeholders the letters V and C, respectively. This test examined explicit verbal sequence knowledge in terms of the letters on the four response keys.

2.1.5. Procedure

At the start of the experiment, participants were told that the experiment would last about 2.5 to 3 h. They were instructed to respond as fast as possible when performing the sequences while not exceeding 6% error (error rates were displayed at end of each subblock). Participants then signed the informed consent form and started with Block 1. Detailed instructions were provided on the computer display.

Table 1 shows an outline of the procedure used in Experiment 1. Blocks 1–6 consisted of two 50-trial sub-blocks separated by a 20-s break. Blocks 2–6 involved sequence practice and were used for the analyses. With 50 trials per sequence per block, this yielded a total of 250 practice trials per sequence. In Experiment 1, the participants carried out the awareness task after the last practice block (Block 6) and before the test phase in Block 7. Block 7 consisted of the aforementioned four 50-trial sub-blocks. The first three sub-blocks were followed by a 20-s break prior to the start of the next sub-block. Each sub-block in the practice and test phases was followed by a display that indicated average RT and error rate. Blocks 1–6 were followed by a 3-min break. After each break, the experimenter entered the cubicle, encouraged the participant to maintain concentration and started the next block.

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[3] The greater the probability of a non-correspondence between stimuli and responses, the smaller the Simon effect (Hommel, 1994; Ridderinkhof, 2002). However, with the current probabilities of 25% and 37% we did not obtain statistically significant effects. Most likely, we did not sufficiently manipulate correspondence likelihood (e.g., Wühr & Heuer, 2015, used 80% vs. 20% corresponding stimulus locations). As this issue does not relate to the main research questions here, we report only the analysis across both groups and ignore this group difference.

Table 1
Overview of the procedure in Experiment 1 in the order of the successive task parts.

| Part	Task description	Purpose
Block 1	Reacting to series of 7 random stimuli Subblock 1: 50 7-element series - 'EURO' displayed at bottom of screen Subblock 2: 50 7-element series - 'EURO' not displayed	Learning the S-R mappings: 'E' = = > ;C key, 'U' = = > ;V key, 'R' = = > ;B key, 'O' = = > ;N key
Blocks 2–6	Practicing 2 discrete 7-key sequences (RSI 0) p(corresponding letter location) = 25%/37% (Footnote 3) 2 × 50 trials/block (total: 250 trials/sequence)	Learning two fixed 7-element keying sequences
Awareness task	Spatial test: click spatial element order Verbal Stimulus test: click stimulus letters (EURO) Verbal Response test: click response key letters (CVBN) - each test: 2 trials, 1 for each of the two practiced sequences	Assessing explicit sequence knowledge in terms of spatial locations, stimulus letters, and keys
Block 7	4 sub-blocks (50 trials/subblock): familiar vs. unfamiliar × 4 vs. 1 placeholder	Assessing the size of the Simon effect as a function of sequence familiarity, relative to a 1-placeholder control condition

2.2. Results

The first two sequences of each sub-block, and the sequences that took more time to execute than the block mean plus 2.5 standard deviations were excluded from the analyses. The effect of correspondence between stimulus and response location – representing the Simon effect – was determined for each sequence position. As the purpose of Block 1 was learning stimulus-response mappings, data from this block are not reported. The results of the F-tests were Greenhouse-Geisser corrected when Mauchley's test of sphericity was significant.

2.2.1. Practice blocks

RTs were analyzed using a within-subjects 5 (Block 2–6) × 2 (Correspondence) × 7 (Position in sequence) ANOVA. Outlier exclusion reduced the number of sequences by 2.7% across the five practice blocks. This ANOVA showed main effects of Block, $F(4,124) = 120.2$, $p < .001$, $\eta_p^2 = 0.79$, indicating a reduction in RT with practice, and Position, $F(6,186) = 49.3$, $p < .001$, $\eta_p^2 = 0.61$, revealing that throughout practice T_1 was relatively long compared to $T_{2–7}$. The significant Block × Position interaction indicated that practice had a different effect on the various elements in the sequence, $F(24,744) = 10.4$, $p < .001$, $\eta_p^2 = 0.25$, confirming the typical finding that T_1, in particular, reduced little with practice.

More important in the context of the present research, the significant Correspondence main effect revealed a 47 ms Simon effect across Blocks 2 through 6 resulting from the responses to corresponding stimulus locations being faster than to non-corresponding stimulus locations, $F(1,31) = 146.0$, $p < .001$, $\eta_p^2 = 0.82$. According to the significant Block × Correspondence interaction, the Correspondence effect was reduced with practice, $F(4,124) = 6.8$, $p = .001$, $\eta_p^2 = 0.18$ (Fig. 2). It amounted to 67, 39, 49, 50, 36 ms in Blocks 2 through 6, respectively. The Correspondence effect reduced significantly from Block 2 to Block 3, $F(1,31) = 10.0$, $p < .004$, $\eta_p^2 = 0.24$, after which it slightly increased again. Importantly, the Simon effect was not eliminated with practice in the sense that the Correspondence effect was still significant in Block 6, $F(1,31) = 40.9$, $p < .001$, $\eta_p^2 = 0.57$, even when T_1 was excluded (given that S_1 could never be ignored anyway), $F(1,31) = 35.7$, $p < .001$, $\eta_p^2 = 0.54$.

A significant Correspondence × Position interaction, $F(6,186) = 12.6$, $p < .001$, $\eta_p^2 = 0.29$, superseded by a significant Block × Correspondence × Position interaction, $F(24,744) = 4.9$, $p < .001$, $\eta_p^2 = 0.14$ (see Fig. 3), indicated that the Correspondence effect differed for the various sequence positions, and that this difference changed with practice. Planned comparison showed that across Blocks 2 through 6 the Correspondence effect was smaller across
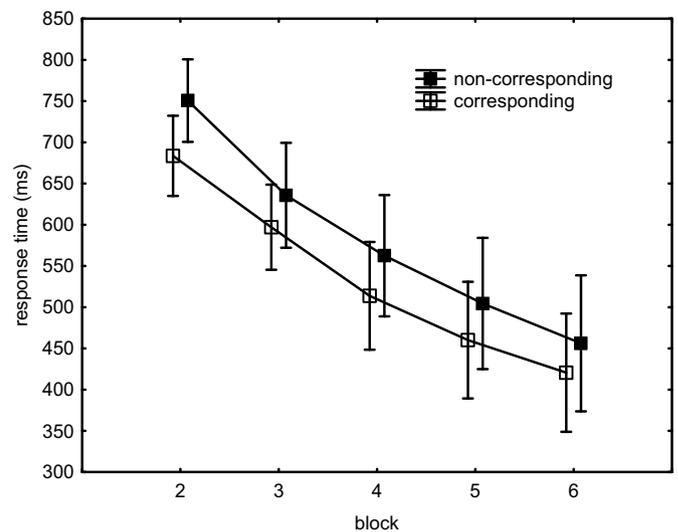
Fig. 2. The Correspondence effect that represents the Simon effect across the 7 sequence positions in Blocks 2 through 6 in Experiment 1 (Block 1 only involved learning the letter-response mappings). Error bars indicate the Standard Error of the Mean (SEM; these values are quite large because they also include the differences across T_2 to T_7, cf. Fig. 3).

T_{234567} (40 ms) than for T_1 (86 ms), $F(1,31) = 28.1$, $p < .001$, $\eta_p^2 = 0.48$. A planned Block × Correspondence × T_1 vs. T_{234567} interaction showed a marginally significant effect, $F(4,124) = 2.0$, $p < .10$, $\eta_p^2 = 0.06$. In contrast to the prediction that the Simon effect would reduce more with practice for T_{234567} than for T_1, the Correspondence effect was reduced more with practice for T_1 than for T_{234567} (T_1: from 102 ms in Block 2 to 52 ms in Block 6; T_{234567}: from 61 ms in Block 2 to 33 ms in Block 6), although in both cases, the Simon effect reduced by almost 50% for T_1 and for T_{23457}.

Error proportions were arcsine-transformed and then submitted to the same repeated-measures ANOVA as used for the RTs (Winer, Brown, & Michels, 1991) with Greenhouse-Geisser corrections where necessary. This 5 (Block) × 2 (Correspondence) × 7 (Position) ANOVA on these error proportions showed a significant Correspondence main effect indicating that corresponding responses involved less errors than non-corresponding responses (1.7% vs. 3.7% per response), $F(1,31) = 153.2$, $p < .001$, $\eta_p^2 = 0.83$. A significant Block effect indicated that error percentage varied somewhat for the various blocks (between 2.4% in Block 2 and 2.9% in Block 6), $F(5,124) = 2.6$, $p < .05$, $\eta_p^2 = 0.08$. The significant Block × Correspondence
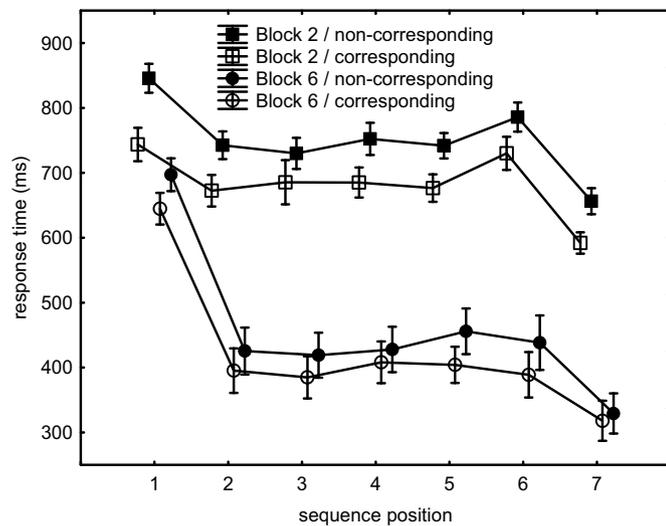
Fig. 3. The effect of Correspondence between response and stimulus locations in Blocks 2 and 6 of Experiment 1 (Blocks 3–5 are not shown for clarity).

interaction revealed that error proportion increased with practice for the corresponding responses, from 1.3% per response in Block 2 to 2.0% in Block 6 whereas it was reduced for non-corresponding responses from 4.3% in Block 2 to 3.7% in Block 6, $F(4,124) = 6.9$, $p < .001$, $\eta_p^2 = 0.19$. Thus, the error data also showed a Simon effect that reduced from a 3.0% error rate difference in Block 2, to 1.7% by Block 6. A significant Position main effect indicated that error percentage was between 2.2% and 3.3% for responses at Positions 1 to 5 and 7, and increased to 4.7% at Position 6, $F(6,186) = 4.7$, $p < .001$, $\eta_p^2 = 0.13$. According to the significant Block × Position interaction, the difference in error proportions increased as a function of Position in later blocks, $F(24,744) = 1.9$, $p = .03$, $\eta_p^2 = 0.06$.

2.2.2. Test block

RTs in the test phase were analyzed using a 2 (Familiarity) × 2 (Placeholder: 1 versus 4) × 2 (Correspondence) × 7 (Position) repeated-measures ANOVA. Outlier removal excluded 3% of the data. The results showed significant main effects of Familiarity, $F(1,31) = 54.3$, $p < .001$, $\eta_p^2 = 0.63$, and Position, $F(6,186) = 74.8$, $p < .001$, $\eta_p^2 = 0.71$, showing that familiar sequences were executed faster than the unfamiliar ones, and that R_1 was especially slow. The significant main effect of Placeholder indicated that RT was 37 ms shorter for 1 compared to 4 placeholders, $F(1,31) = 14.1$, $p < .001$, $\eta_p^2 = 0.31$. A significant Placeholder × Familiarity interaction indicated that the advantage of 1 over 4 placeholders was larger for the unfamiliar as opposed to the familiar sequences, 58 ms vs. 15 ms, $F(1,31) = 6.8$, $p = .01$, $\eta_p^2 = 0.18$.

Correspondence was significant as a main effect, $F(1,31) = 29.0$, $p < .001$, $\eta_p^2 = 0.48$. The effect of Correspondence in the various test conditions can be observed in Fig. 4. The significant Correspondence × Placeholder interaction confirmed that the Correspondence effect only occurred for the 4-Placeholder conditions (4 placeholders: 48 ms vs. 1 placeholder: 7 ms), $F(1,31) = 47.8$, $p < .001$, $\eta_p^2 = 0.61$. Planned comparisons showed that in the 4-Placeholder condition the Correspondence effect was significant in both the unfamiliar and the familiar sequences (56 and 41 ms, resp.), $Fs(1,31) > 30.2$, $ps < .001$, $\eta_p^2s > 0.49$. However, contrary to a reduced Correspondence effect with practice (suggestive of reduced reliance on key-specific stimuli), the Correspondence effect did not differ for familiar and unfamiliar sequences, $F(1,31) = 1.6$, $p = .22$. Additional planned comparisons indicated that the Correspondence effect for the 4-Placeholder condition was a result of slowing of non-corresponding responses relative to the 1-Placeholder condition, $F(1,31) = 28.5$, $p < .001$, $\eta_p^2 = 0.48$,

whereas responses to corresponding stimuli in the 4-Placeholder condition were not different from those in the 1-Placeholder condition, $F(1,31) = 1.1$, $p = .31$.

Position did not interact with Correspondence, $F(6,186) = 1.4$, $p = .24$. Moreover, a planned comparison did not support the prediction that in the 4-Placeholder condition the Correspondence effect for familiar sequences is larger for R_1 than for R_{234567}, $F(1,31) = 3.16$, $p = .09$.

Arcsine-transformed error proportions of Block 7 were analyzed using a 2 (Familiarity) × 2 (Placeholder) × 2 (Correspondence) × 7 (Position) repeated-measures ANOVA. Results showed significant main effects of Familiarity, $F(1,31) = 38.7$, $p < .001$, $\eta_p^2 = 0.56$, and Position, $F(6,186) = 8.1$, $p < .001$, $\eta_p^2 = 0.21$, indicating that error rate was slightly lower in unfamiliar than in familiar sequences (3.2% vs. 4.3% per Position), and varied between 2.7% (at R_7) and 5.4% (at R_6). A significant Placeholder main effect showed that error rate was higher with 1 rather than 4 placeholders, 4.4% vs. 3.2%, $F(1,31) = 19.2$, $p < .001$, $\eta_p^2 = 0.38$. Finally, a significant Familiarity × Correspondence interaction revealed that error rate with corresponding stimuli was not different for familiar and unfamiliar sequences (3.9% vs. 4.0%), but was relatively high for non-corresponding stimuli in familiar sequences (4.7%), and relatively low in unfamiliar sequences (2.6%), $F(1,31) = 17.5$, $p < .001$, $\eta_p^2 = 0.36$.

2.2.3. Awareness

Reproduction by each participant of his or her two sequences in the awareness task – in terms of the number of correct sequences and the number of correct sequence elements – was generally poorer in the Verbal Response test than in the Spatial and Verbal Stimulus tests. The number of correctly reproduced sequences in the Spatial test amounted to 18 (i.e., 28% correct sequences of the 64 reproduced sequences), in the Verbal Response test this was 7 (11%), and in the Verbal Stimulus test 19 (30%). McNemar's exact χ^2 test showed that the number of correct sequences was significantly lower in the Verbal Response test than in the Spatial and Verbal Stimulus tests, $ps < .02$.

The number of correct elements per sequence position for each participant (ranging from 0 to 2) was analyzed with a nonparametric 3 (Test) × 7 (Position) ANOVA using the nparLD package in RStudio with the ANOVA-Type Statistic (ATS; Noguchi, Gel, Brunner, & Konietschke, 2012). It showed a significant Test main effect (Spatial: 1.12, Verbal Response: 0.98, Verbal Stimulus: 1.28), $ATS(1.5) = 5.24$, $p = .01$.[4] It further showed by way of a significant Position main effect that the number of correct elements was somewhat lower after R_3 (1.28, 1.30, 1.04, 1.09, 1.00, 1.08, and 1.07), $ATS(4.3) = 2.74$, $p = .02$. Pairwise comparisons of the three awareness tests showed that performance was better in the Verbal Stimulus task than in the Spatial task, $F(1) = 4.52$, $p = .03$, and in the Verbal Response task, $ATS(1) = 15.2$, $p < .001$. The difference between the Spatial and the Verbal Response tasks was not significant, $ATS(1) = 1.4$, $p = .24$. The sum of the of Simon effects across T_2-T_7 of the last practice block did not correlate significantly with the awareness tests, $rs(N = 32) < -0.32$, $ps > .09$. The only marginally significant correlation ($p = .08$) occurred with the Verbal Response task, which is the awareness test that was performed most poorly.

In short, the awareness task showed that participants possessed some explicit knowledge of the sequences in terms of stimulus locations and stimulus letters but had little explicit knowledge of the keys they had been pressing. These three measures for awareness did not show a significant correlation with the Simon effect at the end of practice, and therefore do not support the possibility that the Simon effect was smaller in more aware participants.

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[4] Effect size computations have not yet been developed for this type of ANOVA.
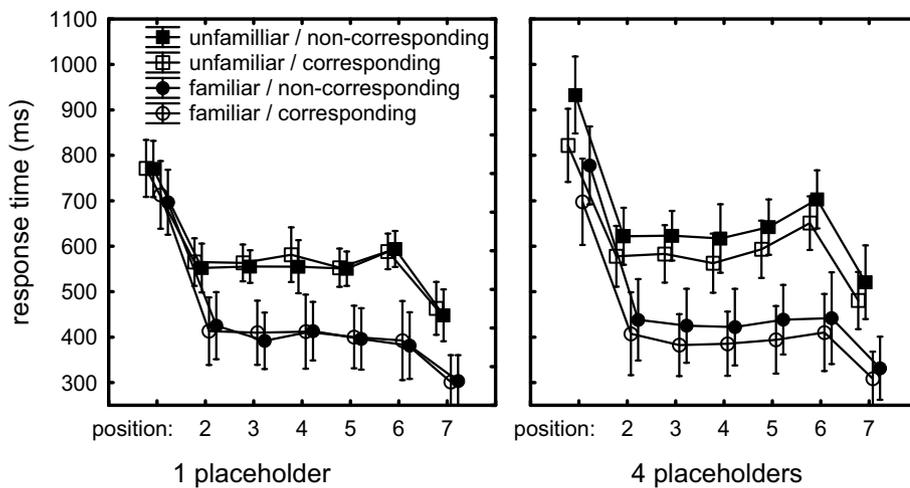
Fig. 4. The effect of correspondence in the test phase (Block 7) of Experiment 1 as a function of sequence familiarity, number of placeholders, and sequence Position. Note that the 1-Placeholder condition is used as a control condition in which corresponding and non-corresponding conditions were determined by the same random allocation algorithm as in the 4-Placeholder condition which did not actually affect stimulus location. Error bars indicate the Standard Error of the Mean (SEM).

2.3. Discussion

The main purpose of Experiment 1 was to examine whether the contribution of key-specific stimuli to executing sequences is less for practiced than for novel sequences. To that end, we used the Simon effect as an index for the processing of the key-specific stimuli. The results showed a lasting Simon effect despite the obvious development of sequencing skill. Comparison of the 4- and 1-Placeholder conditions showed that, like in choice RT tasks (Lu & Proctor, 1995), the Simon effect in the DSP task was caused by response slowing when the stimulus was displayed at a non-corresponding location, and not by a benefit of displaying the letter stimuli at corresponding locations.

The data are almost entirely in line with the predictions of the slow-sequencing system hypothesis. The results not only showed a similar Simon effect in RTs in familiar and unfamiliar sequences in the test phase, but also confirmed the minor initial reduction of the Simon effect during practice after which it remained stable. The Simon effect emerged also in the error rates of the practice phase. The practice phase data further confirmed the prediction that the Simon effect would remain larger for R_1 than for the other responses across practice, but a larger Simon effect in R_1 was not observed in the 4-Placeholder test conditions. Perhaps the Simon effect in the test phase was relatively small in R_1 because participants had learned to counteract the effect of irrelevant spatial codes at R_1 while this was harder for later responses due to the cognitive load of sequence execution.

The data showed that the lasting Simon effect occurred across all participants who on average had moderate sequence awareness. In principle this finding is consistent with the earlier findings in the serial RT task study where the Simon effect persisted in unaware participants (Koch, 2007; Tubau & López-Moliner, 2004). In these serial RT task studies awareness probably allowed aware participants to disengage attention from the stimulus display area for parts of, or for the entire, sequence (Belopolsky et al., 2010; Theeuwes, 2010; Tubau & López-Moliner, 2004) because aware participants knew they could rely on their (explicit and/or implicit) sequence knowledge. However, in the present study correlations did not show a smaller Simon effect for more aware participants. In the DSP task it is indeed less likely than in the serial RT task that awareness caused participants to ignore key-specific stimuli. First, when performing DSP sequences participants always have to attend to the first stimulus and even fully aware participants are therefore likely to also perceive a few or all ensuing stimuli. Second, earlier studies suggested that the high execution rates of DSP sequences with their 0-RSIs and heavy reliance on implicit sequence knowledge prevent even fully aware participants from applying their explicit sequence knowledge (Verwey, 2015; Verwey, Groen, & Wright, 2016). So, in the DSP task awareness is unlikely to make participants ignore the key-specific stimuli.

3. Experiment 2

While Experiment 1 showed that participants continue using key-specific stimuli, this does not necessarily mean that this was caused by attentional capture by these stimuli. Participants may have intentionally processed the letter stimuli because that seemed beneficial to them (Verwey, in press). In Experiment 2 we therefore examined whether the continued reliance on key-specific stimuli in Experiment 1 had been automatic (i.e., the *automatic-processing hypothesis*) or intentional (the *intentional-processing hypothesis*). To explore this, we tested whether inappropriate stimuli slow responses in two distinct situations, when useful (and correct) letters and useless (unchanging) letters are displayed at corresponding and non-corresponding locations, and when correct and incorrect letters are displayed at a single location. This was expected to show whether participants are forced to attend to stimuli, with and without attentional capture.

After having practiced the same two 7-element DSP sequences as in Experiment 1 participants again performed the practiced sequences in four test conditions. The first two test conditions involved displaying each stimulus in one of the four placeholders. The *4-Placeholder/Letter* condition included displaying stimulus letters at corresponding ($p = 25\%$) and non-corresponding locations ($p = 75\%$). In the important *4-Placeholder/X* condition, the first letter stimulus was followed by X's displayed at a location corresponding to that of the response with a probability of 25%. A similar Simon effect in the two conditions would show that even the often-harmful X's cannot be ignored. This would support the automatic-processing hypothesis which is based on the notion that visuospatial attention is automatically attracted. Finding no Simon effect in the 4-Placeholder/X condition would show that participants can ignore key-specific stimuli that involve a luminance change, just like isoluminant stimuli (Verwey, in press). This would support the intentional-processing hypothesis.

One of the next two test conditions, the *1-Placeholder/Letter* condition, involved displaying in a single placeholder incorrect letters in 75% of the cases (after the first stimulus). This can be considered a non-spatial version of the Simon effect because correct and incorrect letters are displayed. Slow responses after incorrect key-specific stimuli would demonstrate that even with a single placeholder, participants cannot disengage attention after having identified the first stimulus. In the *1-Placeholder/X* condition, only neutral X's were displayed in a single placeholder after the first letter stimulus. This condition was meant to demonstrate that enough sequencing skill had developed to allow sequence execution without guiding stimuli. It also provided baseline RTs for the situation that participants in the 1-Placeholder/Letter condition would ignore letters past the first.

Experiment 2 also examined the race assumption by testing the

prediction that the Simon effect would be larger if a response is triggered more slowly by the sequencing systems because that would increase the contribution of S-R translation which is responsible for the Simon effect. This is a strong prediction as choice RT studies usually show that the Simon effect is smaller for slower responses (De Jong et al., 1994; Eimer et al., 1995). We induced slowed R_5 triggering by the sequencing systems by having participants practice prestructured sequences in which a pause occurs between R_4 and S_5, and then in the test phase remove that pause. This is known to yield a slow R_5 that is attributed to concatenating successive sequence segments (Verwey, 1996; Verwey, Abrahamse, & De Kleine, 2010; Verwey, Abrahamse, De Kleine, & Ruitenberg, 2014; Verwey, Abrahamse, & Jiménez, 2009).

3.1. Method

Twenty-four students that did not participate in Experiment 1 (between 18 and 25 years, mean age 19.5 years, 18 females) took part in Experiment 2. This sample size was based on a power analysis using the $\eta_p^2 = 0.13$ observed in Experiment 1 for the Correspondence effect in the Familiar sequence, 4-Placeholder condition. Together with $\alpha = 0.05$, and power $1 - \beta = 0.85$ and 7 repeated measurements (in a sequence), GPower 3.1 indicated a sample size of 20 participants for a repeated measures ANOVA. This was rounded up to 24 to allow full counterbalancing in Experiment 2. All participants were students at the University of Twente. Informed consent was obtained from all participants, and the study was approved by the Ethics Committee of the Faculty of Behavior, Management, and Social Sciences at the University of Twente. The experiment ran on a Windows 10 Enterprise (64 bit) Dell Optiplex 750 Computer using *E*-prime 2.0, with an AOC Freesync 144 Hz monitor.

Sequence task

Table 2 provides an overview of the procedure used in Experiment 2. The practice phase was largely the same as in Experiment 1 including 250 practice trials per sequence in Blocks 2 to 6. However, this time all participants practiced with a 25% corresponding stimulus location likelihood. Also, there was an interval of 500 to 2000 ms between R_4

and S_5 during practice that had a non-aging distribution to reduce predictability (Gottsdanker, Perkins, & Aftab, 1986). The test phase in Block 7 included four sub-blocks that were separated by 20 s. In the test phase the interval between R_4 and S_5 was always zero.

The order of the first two sub-blocks in the test block was counterbalanced across participants. These sub-blocks involved display of one of the familiar letters (E, U, R, O) in one of four placeholders. S_1 was the normal letter stimulus participants had been practicing with, and both conditions involved 25% corresponding and 75% non-corresponding stimulus locations. One sub-block involved the *4-Placeholder/Letter* condition which mimicked the practice phase. The other subblock contained the *4-Placeholder/X* condition in which S_2 to S_7 always consisted of X's at corresponding and non-corresponding locations, and participants were to determine R_2-R_7 from memory.

The third and fourth sub-blocks were performed also in a counterbalanced order but contained only 1 placeholder in the center of the display. In both sub-blocks, sequences started with one of the two letter stimuli to indicate the sequence. In the sub-block with the *1-Placeholder/Letter* condition this continued with familiar letter stimuli, but only 25% of the letters was associated with the required response. The remaining 75% involved one of the other three other letters of the set, thus mimicking the 25% corresponding location condition with 4 placeholders. The other sub-block contained the *1-Placeholder/X* condition in which, following the regular S_1 letter, only a single × was displayed. In both conditions, participants were instructed to produce the sequence indicated by the first letter, S_1. To prevent a beneficial effect of performing the awareness task on keying performance in, especially, the conditions that only involved display of the X's, in Experiment 2 the awareness task was carried out after the test phase in Block 7. The entire experiment took about 3 h.

3.2. Results

3.2.1. Practice blocks

After removal of outliers (removing < 3% of the data) and the first two sequences of each sub-block, we subjected the RTs in the practice phase to a 5 (Block: 2–6) × 2 (Correspondence) × 7 (Position) within-

Table 2
Overview of the procedure in Experiment 2 in the order of the successive parts.

| Part	Task description	Purpose

Block 1	Reacting to series of 7 random stimuli
	Subblock 1: 50 7-element series
	
	   - 'EURO' displayed at bottom of screen
	Subblock 2: 50 7-element series
	
	   - 'EURO' not displayed
		Learning the S-R mappings
		'E' = = > ;C key, 'U' = = > ;V key,
		'R' = = > ;B key, 'O' = = > ;N key

Blocks 2–6	Practicing 2 discrete 7-key sequences (RSI 0, R_4S_5I: 500–2000 ms) p(corresponding letter location) = 25% 2 × 50 trials/block (total: 250 trials/sequence)	Learning two fixed 7-element keying sequences
Block 7	Sub-blocks 1 & 2 (25% corresponding stimulus locations) −4-Placeholder/Letter letter at each sequence position (cf. practice) −4-Placeholder/X S_1: letter, S_2–S_7: 'X' Sub-blocks 3 & 4 (letters in one placeholder) −1-Placeholder/Letter S_1: correct letter, S_2–S_7: P(correct letter) = 25% −1-Placeholder/X S_1: correct letter, S_2–S_7: 'X'	Assessing the effect of (non-) corresponding locations with 4-placeholders, and (non-) corresponding letters with 1 placeholder

Awareness task	Spatial test: click spatial element order
	Verbal Stimulus test: click stimulus letters (EURO)
	Verbal Response test: click response key letters (CVBN)
	
	   - each test: 2 trials, 1 for each of the two practiced
	     sequences
		Assessing explicit sequence knowledge in terms of spatial locations, stimulus letters, and keys
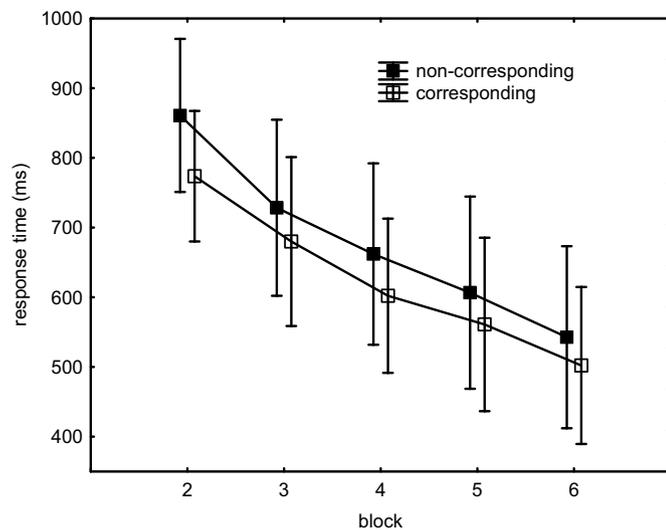
Fig. 5. The Correspondence effect across all sequence positions in Blocks 2 through 6 in Experiment 2. Error bars indicate the Standard Error of the Mean (SEM).
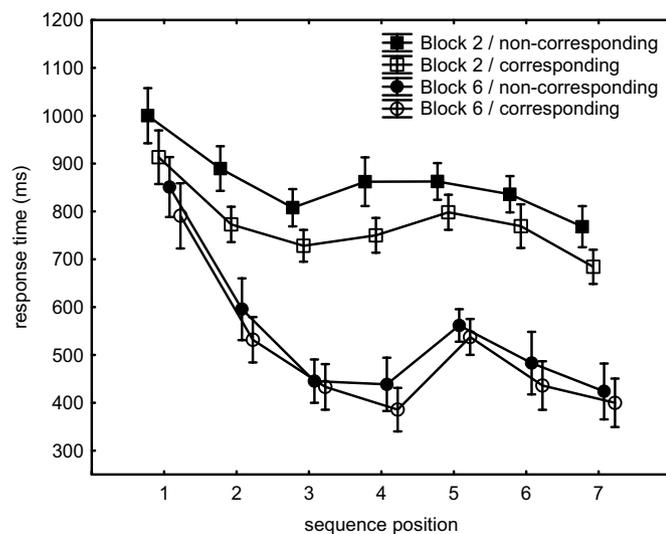

Fig. 7. The Correspondence effect in the two 4-Placeholder test conditions of Experiment 2. Error bars indicate the Standard Error of the Mean (SEM).

Fig. 6. The Correspondence effect in Blocks 2 and 6 of Experiment 2 (Blocks 3–5 are not shown for clarity). Error bars indicate the Standard Error of the Mean (SEM).

subjects ANOVA. This ANOVA showed significant main effects of Block, $F(4,92) = 45.1$, $p < .001$, $\eta_p^2 = 0.66$, indicating a reduction in RT across Blocks 2 through 6 (Fig. 5), and Position, $F(6,138) = 33.0$, $p < .001$, $\eta_p^2 = 0.59$, revealing a relatively slow R_1 and R_5. The significant Block × Position interaction confirmed that R_1 and R_5 in particular exhibited little reduction with practice (Fig. 6), $F(24,552) = 6.1$, $p < .001$, $\eta_p^2 = 0.21$. While this is typical for R_1 it also not that surprising for R_5 given that in the practice phase this specific response always entailed some time uncertainty.

The significant Correspondence main effect revealed a 54-ms Simon effect reflected in slower response times when the stimulus location did not correspond with the response location, $F(1,23) = 69.1$, $p < .001$, $\eta_p^2 = 0.75$. According to a significant Correspondence × Block interaction, the Simon effect was reduced with practice (Fig. 5), $F(4,92) = 8.6$, $p < .001$, $\eta_p^2 = 0.27$. The reduction in the Correspondence effect occurred primarily from Block 2 to 3 (from 87 to 49 ms, respectively), $F(1,23) = 14.0$, $p = .001$, $\eta_p^2 = 0.38$ and remained more or less stable across the remaining blocks, $F(3,69) = 2.1$, $p = .11$. It should be noted that the Correspondence effect was still significant at
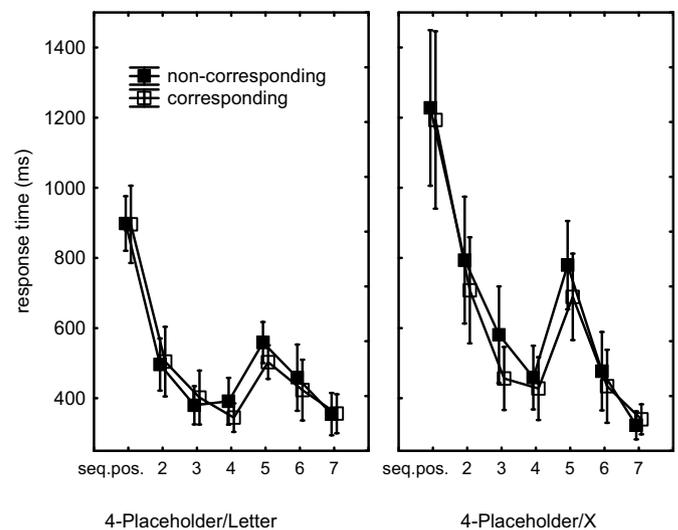
Block 6, $F(1,23) = 19.1$, $p < .001$, $\eta_p^2 = 0.45$, even when disregarding T_1, $F(1,23) = 11.1$, $p = .003$, $\eta_p^2 = 0.33$. These effects mirror findings reported in Experiment 1. Correspondence did not interact with Position (for individual sequence positions it varied between 74 ms at R_2 and 46 ms at R_7, $F(6,138) = 1.4$, $p = .22$. The Correspondence × Block × Position interaction failed to reach significance, $F(24,552) = 0.96$, $p = .51$.

The same ANOVA on arcsine transformed error proportions showed significant main effects of Block, $F(4,92) = 5.9$, $p < .001$, $\eta_p^2 = 0.20$, and Position, $F(6,138) = 4.7$, $p < .001$, $\eta_p^2 = 0.17$. These effects indicated a gradual increase in error rate from Block 2 to 6, from 1.6% per key to 2.3% per key, and that error rate varied across keys: lowest at R_3 (1.4%) and highest at R_2 and R_7 (both 2.5%). Congruent with the Simon effect on RT, more errors were made to non-corresponding than to corresponding stimuli (2.6% versus 1.4%), $F(1,23) = 101.3$, $p < .001$, $\eta_p^2 = 0.81$. According to the significant Block × Correspondence interaction, $F(4,92) = 6.8$, $p < .001$, $\eta_p^2 = 0.23$, error rate increased across blocks for the corresponding responses (Block 2: 0.7%, Block 6: 2.1%) while it remained quite stable across blocks for the non-corresponding responses (Block 2: 2.4%, Block 6: 2.8%). Thus, the error data also revealed a Simon effect that was reduced from 1.7% error rate difference in Block 2 to a 0.7% error rate difference by Block 6.

3.2.2. The test block
3.2.2.1. The 4-Placeholder conditions. Response times of correctly executed sequences in the 4-Placeholder/Letter and 4-Placeholder/X conditions are depicted in Fig. 7. Response times at Positions 2 to 7 were subjected to a 2 (Stimulus: letter vs. X) × 2 (Correspondence) × 6 (Position: 2–7) within-subject ANOVA. T_1s were excluded because the 4-Placeholder/X condition S_1 still involved a letter stimulus. Five of the 24 participants were not involved in the analysis because they could not execute the sequences without external guidance in the 4-Placeholder/X condition.[5]

The significant Correspondence main effect across T_{234567} amounted

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[5] Participants who did not properly produce their sequences without external guidance were removed for statistical reasons, but also because this eliminated participants who apparently did not develop sufficiently strong sequence representations and were therefore unsuited to test the hypotheses. It is not unusual that a few participants cannot produce their sequences after even 500 practice trials in response to just the first stimulus (e.g., Abrahamse et al., 2013).

to 38 ms (504 vs. 466 m), $F(1,18) = 6.2, p = .02, \eta_p^2 = 0.26$. The lack of a significant Stimulus × Correspondence interaction indicated that the Simon effect did not differ for the letters and the neutral X's, $F(1,18) = 18.0, p = .20$. Planned comparisons showed that responses to non-corresponding stimulus locations were slower than to corresponding stimulus locations in both the 4-Placeholder/Letter condition (18 ms), $F(1,18) = 5.1, p = .04, \eta_p^2 = 0.22$, and the 4-Placeholder/X condition (59 ms), $F(1,18) = 3.9, p = .06, \eta_p^2 = 0.18$.

The pause that had preceded S_5 during practice induced the expected slowing of R_5 in the test phase. A significant Position main effect indicated that this was caused in part by a relative long T_5 (Fig. 7, about 630 ms versus < 460 ms for T_{3467}), $F(5,90) = 7.0, p = .001, \eta_p^2 = 0.28$. Planned comparisons confirmed that T_5 was longer than the average of T_4 and T_6 in both 4-Placeholder conditions, $Fs(1,18) > 7.0, ps < .02, \eta_p^2 s > 0.28$. The prediction of greater slowing of R_5 than of R_{23467} for a non-corresponding rather than a corresponding stimulus location (i.e., a larger Simon effect) was observed across the letter and × conditions (from 32 ms across R_{23467} vs. 73 ms for R_5), but it failed to reach significance, $F(1,18) = 1.1, p = .31$. More detailed analyses did show that the Simon effect increased in the 4-Placeholder/Letter condition from 10 ms for R_{23467} to 56 ms for R_5, the latter of which approached significance, $F(1,18) = 3.6, p = .07, \eta_p^2 = 0.17$. A similar increase was observed in the 4-Placeholder/X condition, from 54 ms for R_{23467} to 90 ms for R_5, but in this case the effect was far from significant, $F(1,18) = 0.3, p = .61$. So, the predicted Simon effect increases at R_5 were evident but not sufficiently robust to reach traditional levels of statistical significance.

A significant Stimulus main effect showed that responses were substantially faster to letters as opposed to just X's (431 ms vs. 539 ms), $F(1,18) = 5.7, p = .03, \eta_p^2 = 0.24$. A significant Stimulus × Position interaction revealed that the advantage of using letters to signal responses amounted to 251 ms, 128 ms, 75 ms, 203 ms, 15 ms, −24 ms for response R_2-R_7, respectively, $F(5,90) = 3.8, p = .03, \eta_p^2 = 0.17$. These results suggest that the advantage of the letters was reduced towards the end of each 3-element segment. This was confirmed by a separate ANOVA that examined data in which the 6 key positions were partitioned into two segments with 3 positions which revealed that the advantage of the letter over the × condition was reduced towards the end of the segment, from 227 ms (for R_2/R_5) and 71 ms (R_3/R_6) to 26 ms (R_4/R_7), $F(2,36) = 4.7, p = .02, \eta_p^2 = 0.21$.

Arcsine transformed error proportions were subjected to the same 2 (Stimulus) × 2 (Correspondence) × 6 (Position) within-subject ANOVA. It showed significant main effects of Stimulus, $F(1,22) = 7.2, p = .01, \eta_p^2 = 0.25$, and Correspondence, $F(1,22) = 13.8, p = .001, \eta_p^2 = 0.39$, indicating more erroneous responses with 4-Placeholder/X stimuli (12.2% per key) than with letters in 4-Placeholder/Letter (2.3%) as well as more errors for non-corresponding as opposed to corresponding responses (7.8% vs. 6.7%). The significant Position main effect, $F(6,132) = 4.9, p < .001, \eta_p^2 = 0.18$, and Stimulus × Position interaction, $F(6,132) = 4.4, p < .001, \eta_p^2 = 0.17$, showed that error rate per key increased with sequence position from about 2% at R_1 to about 3% at R_7 in 4-Placeholder/Letter condition, whereas in 4-Placeholder/X condition error rate increased from 3% for the letter at R_1 to about 14% at Position 4 and subsequent positions. This pattern was unaffected by Correspondence.

3.2.2.2. The 1-Placeholder conditions. Response times of correctly executed sequences in the 1-Placeholder/Letter and in the 1-Placeholder/X conditions were analyzed with a 3 (Stimulus: correct letter, incorrect letter, neutral X) × 6 (Position: 2–7) within-subject ANOVA. For this analysis, three participants were excluded due to missing data (see Footnote 5). A Position main effect, $F(5,100) = 3.2, p = .04, \eta_p^2 = 0.14$, was the only significant effect to be observed from this analysis. Visual inspection of the data in Fig. 8 confirms that the RT pattern across positions was very similar for the three Stimulus conditions. Neither the Stimulus main effect, $F(2,40) = 0.8, p = .47$,
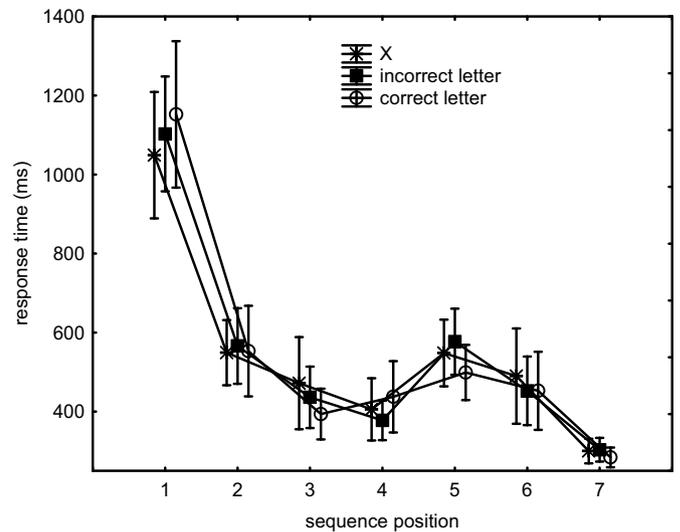

Fig. 8. The effect of stimulus letter in the two 1-Placeholder conditions in Experiment 2. Error bars indicate the Standard Error of the Mean (SEM).

nor the Stimulus × Position interaction reached statistical significance, $F(10,200) = 1.0, p = .41$, indicating that letters beyond Position 1 were not used for sequence execution.

Across the three Stimulus conditions, T_5 was marginally slower than T_{23467}, $F(1,20) = 3.4, p = .08, \eta_p^2 = 0.14$. Consistent with the possibility that S_5 was relied upon for initiating the second motor chunk, the difference between T_5 and T_{23467} was significant when incorrect letters were displayed, $F(1,20) = 6.0, p = .02, \eta_p^2 = 0.23$, but not for correct letters, $F(1,20) = 1.3, p = .26$. This T_5 vs. T_{23467} difference was significantly greater with incorrect than with correct letters, $F(1,20) = 9.9, p = .005, \eta_p^2 = 0.33$, implying display of letters affected sequence execution only at Position 5.

Subjecting arcsine transformed error proportions to the above mentioned within-subjects 3 (Letter) × 7 (Position) ANOVA showed only a significant main effect of Position, $F(6,132) = 5.1, p < .001, \eta_p^2 = 0.19$. This indicated an error rate increase from 2.8% at R_1 to 9.6% at R_5 and a subsequent reduction to 8.0% at R_7. Across all three Stimulus conditions error rate was higher at R_5 than at R_{23467}, $F(1,22) = 10.2, p = .004, \eta_p^2 = 0.32$. Mean error rate per position did not show a clear response conflict reflected in the similar error rate for the three Stimulus conditions (correct letter: 7.2%, incorrect letter: 8.4%, neutral stimulus: 6.0%), $F(2,44) = 0.70, p = .50$.

3.2.2.3. 4-Placeholder versus 1-Placeholder. To assess the effects of the number of placeholders with the uninformative X's, a 3 (Placeholder condition: 4-Placeholder/non-corresponding, 4-Placeholder/corresponding, 1-Placeholder) × 6 (Position: 2–7) within-subject ANOVA on response times was conducted. Five of the 24 participants were excluded because they did not execute the sequences correctly without external guidance. A significant Placeholder main effect, $F(2,36) = 7.4, p = .007, \eta_p^2 = 0.29$, indicated that responses were fastest in the 1-Placeholder condition (403 ms), and slower in the 4-Placeholder/corresponding and the 4-Placeholder/non-corresponding × conditions (509 ms and 569 ms, resp.). Planned comparisons, indicated that the differences between the 1-Placeholder and each of the 4-Placeholder conditions was also significant, $F's(1,18) > 7.2, p's \leq .01, \eta_p^2 s > 0.30$. The Placeholder × Position interaction was not significant, $F(10,180) = 2.4, p = .07, \eta_p^2 = 0.12$, but the benefit of the 1-Placeholder condition, relative to the two 4-Placeholder conditions, was especially large for T_5 relative to T_{23467}, $F(1,18) = 8.4, p = .01, \eta_p^2 = 0.32$.

3.2.3. Awareness

The number of correctly reproduced sequences in the Spatial test amounted to 36 (of the 48 sequences that the 24 participants reproduced in total, i.e., 75% correct sequences), in the Verbal Response test this number was 9 (i.e., 19% correct), and for the Verbal Stimulus test, 23 (48% correct). McNemar's exact χ^2 test for small frequencies showed that the number of correct sequences was different in all three pairwise test comparisons, p's < .003.

A nonparametric 3 (Test) × 7 (Position) ANOVA on number of correct elements per sequence position in the two sequences with R's nparLD analysis (scale: 0–2) confirmed that the difference between the 3 awareness tests was significant (Spatial: 1.66, Verbal Response: 1.09, Verbal Stimulus: 1.45), ATS(1.8) = 17.4, p < .001. Again, pairwise comparisons of the three tests were all significant, ATS's(1) > 10.3, p's ≤ .001. In contrast to Experiment 1, the Position main effect was not significant, ATS(4.8) = 1.5, p = .19. Like in Experiment 1, the size of Simon effect across T_2-T_7 in the last practice block did not correlate significantly (and now only positively) with the awareness tests, rs (N = 24) < 0.39, ps > .07. Again, the highest correlations occurred with the Verbal Response task which showed poorest performance.

In short, in Experiment 2, participants were especially good at reproducing their sequences in the Spatial test, quite good in the Verbal Stimulus test, and poor in the Verbal Response test. While not statistically significant, the correlations were in the direction of more aware participants having a larger instead of a smaller Simon effect in the last practice block.

3.3. Discussion

To test the automatic-processing hypothesis, we examined whether key-specific stimuli are ignored when they are often harmful, and participants have no reason to attend to them. We examined this with stimulus display at four locations and at one location to determine whether perhaps another mechanism than attentional capture would be responsible for ignoring the stimuli. Additionally, we tested the race assumption by determining whether slow R_5 concatenation responses show a relatively large Simon effect.

Both 4-Placeholder conditions showed a Simon effect that was not smaller in the 4-Placeholder/X than in the 4-Placeholder/Letter condition. This confirms that in both 4-Placeholder conditions attention was automatically drawn to the stimulus location and primed the response at the spatially corresponding location (e.g., Van der Lubbe et al., 2012; Yantis & Jonides, 1984). As this occurred even in the condition with harmful X's at non-corresponding locations this confirms that visuospatial attention was captured by displaying a stimulus, irrespective of its content.

The 1-Placeholder conditions showed no general RT differences for correct letter, incorrect letters and neutral X's. Basically, this supports the claim of the intentional-processing hypothesis that stimuli can be ignored when displayed at one location. However, further scrutiny showed that the relatively slow R_5 in the 1-Placeholder/Letter condition did show that incorrect letters yielded slower responding than correct letters. This demonstrates that participants had not disengaged their attention from the stimulus display area. In retrospect, the rapid display of letters at a single location probably induced an attentional blink (e.g., Raymond, Shapiro, & Arnell, 1992), and only the relatively long display of S_5 allowed identification of the letter used as S_5. These results demonstrate that even in the 1-Placeholder conditions participants did not disengage attention from the area where the stimuli were displayed. This suggests that, perhaps due to the cognitive load of the sequencing task, participants did not quickly disengage attention from the stimulus display area after S_1 display.

With respect to the race assumption, it is important that the 4-Placeholder/Letter condition showed that the Simon effect was 46 ms larger for R_5 than for R_{23467} in the prestructured sequences of Experiment 2 and this difference approached statistical significance. In the 4-Placeholder/X condition, the Simon effect was 36 ms larger at R_5 but this increase was not significant (see Fig. 7). While not statistically robust, we consider these findings noteworthy because with the present RTs of 500 to 600 ms the Simon effect is known to have entirely vanished in choice RT tasks (De Jong et al., 1994; Eimer et al., 1995). Similarly, the 1-Placeholder condition showed that when the sequencing systems had slowed at R_5, incorrect letters significantly increased R_5. Together, these findings provide converging support for the assumption that S-R translation had indeed been racing with the sequencing systems.

An unanticipated observation was that the higher execution rate with letter stimuli than with X's in the 4-Placeholder conditions was reduced towards the end of each sequence segment, from R_2 to R_4 and from R_5 to R_7. These data suggest a decreasing reliance on key-specific stimuli towards the end of each sequence segment. Perhaps participants managed to disengage attention by the end of each segment and relied more on the sequence representations. However, they then had to rapidly re-attend to S_5 again. More likely, therefore, is that sequence representations become more dominant with successive positions because activation accumulated across successive elements in the sequence representations (MacKay, 1982; Verwey, 1994; Verwey & Abrahamse, 2012).

Finally, awareness as indicated by percentage of fully correct sequence reproduction in the Spatial test was with 75% clearly higher than in Experiment 1 (where it amounted to 28%). This was the case also for the Verbal Stimulus (48% vs. 30% in Experiment 1) and the Verbal Response tests (19% vs. 11%). We attribute the higher awareness in Experiment 2 to the awareness task following the test phase, instead of preceding it like in Experiment 1. Especially the 4- and 1-Placeholder/X conditions probably encouraged participants to develop explicit knowledge (as suggested also by data reported in Verwey, in press). This improved especially explicit sequence knowledge in terms of response locations. Most importantly, Experiment 2 again did not show any indication that awareness was associated with a reduced Simon effect (as was the case with the serial RT task, Koch, 2007; Tubau & López-Moliner, 2004).

4. General discussion

In the present study we examined whether the contribution of key-specific stimuli reduces and eventually vanishes with practice, as suggested by models of discrete sequencing skill (Abrahamse et al., 2013; Verwey et al., 2015), or whether these stimuli continue to be processed as suggested by visuospatial attention attraction (e.g., Van der Lubbe et al., 2012; Yantis & Jonides, 1984). We used the Simon effect as an index for the contribution of key-specific stimuli to sequence execution. Experiment 1 confirmed the expectation we advanced in the Introduction that the Simon effect would occur in each response of the keying sequences. In fact, the Simon effect emerged in error rates too. The slow-sequencing system hypothesis – stating that S-R translation would not be overruled by sequencing systems – was supported by two findings. As predicted, in both experiments the Simon effect reduced somewhat in early practice but remained stable with further practice. Also, in Experiment 1 the Simon effect was not smaller for the familiar than for unfamiliar sequences.[6] Experiment 2 then confirmed the

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[6] Given that the Simon effect reduces with longer RTs (e.g., Simon et al., 1976), one could argue that not finding a smaller Simon effect in the faster familiar than in the slower unfamiliar sequences does indicate a smaller reliance on the key-specific stimuli in familiar than in unfamiliar sequences. This notion receives support from the significant reduction of the Simon effect across the initial practice blocks of both experiments. Importantly, the practice phase of both experiments showed that the Simon effect reduction with practice stopped after Block 3. This confirms that participants continued to process key-specific stimuli, but in line with a race model the reliance on key-specific stimuli may have indeed been somewhat less with familiar sequences.

automatic-processing hypothesis stating that the luminance change associated with display of the key-specific stimuli automatically attracts visuospatial attention and primes the spatially compatible response (e.g., Van der Lubbe et al., 2012; Yantis & Jonides, 1984). This was indicated by the finding in the 4-Placeholder/X condition that the Simon effect occurred even when harmful X's followed the first imperative stimulus.

The 1-Placeholder test condition of Experiment 2 was included to examine whether disengaging attention may be specific for displaying stimuli at different locations or occurs also with stimulus display at a single location. In hindsight the high display rate in the 1-Placeholder condition probably did not allow participants to identify individual letters after the first due to an attentional blink. Still, there was one exception. Responding was slower with incorrect than with correct letters for the already slow concatenation response R_5. This demonstrates that attention had not been disengaged from the stimulus display area even when the stimuli past the first were harmful. Perhaps the minor luminance changes associated with the rapid serial display of letters in a single location still captured visual attention. Also, attentional disengagement may have been counteracted by the cognitive demands of sequence executing. This could explain also why in the 4-Placeholder/X condition participants did not disengage attention from the stimulus display area after identification of S_1. So, the data indicate that in DSP tasks participants do not move away their visuospatial attention from the stimulus display area, even when later stimuli may be harmful.

Experiment 2 also provided support for the assumption that S-R translation and sequencing systems are racing to trigger each next response. This is a direct confirmation that with practice the S-R translation system remains active despite concurrent activity of (central-symbolic and motor chunking) sequencing systems, and that S-R translation is not outrun by these sequencing systems. Potentially, stimulus display could have captured attention without affecting sequence execution because S-R translation was entirely outrun by especially the fast motor chunking system. Slowing of R_5 by an incorrect letter in the 1-Placeholder/Letter condition shows that this did not happen. Still, Experiment 2 did show that the beneficial effect of letters over X's reduced at the end of both sequence segments. Probably the sequencing systems become faster towards the end of a segment because they benefit from activation accumulating across successive elements in the sequence representations (MacKay, 1982; Verwey, 1994; Verwey & Abrahamse, 2012). Given the short time between successive stimuli, we consider it unlikely that the reducing benefit of letter display towards the end of each segment was caused by participants rapidly disengaging attention from the stimulus display area during the first segment (Belopolsky et al., 2010; Theeuwes, 2010), who then quickly re-engaged attention to S_5 processing.

The design of both experiments allowed us to assess awareness separately in terms of response locations, stimulus letters, and the letters of the keys on the computer keyboard that had been pressed. The computerized awareness task we used was based on the assumption that explicit knowledge can be assessed best when the response modality differs from that used for executing the keying sequences, as that limits the use of implicit motor sequence knowledge (Baars, 1983; Rünger & Frensch, 2010; Verwey & Dronkers, 2019). The results of the three awareness tests show that explicit sequence knowledge primarily involved response locations and much less the letters of the keys pressed. Explicit knowledge of the stimulus letters was quite high too, but this may have been due to the need to respond to letter stimuli. In any case, these findings confirm that participants in the DSP task are able to also develop verbal sequence knowledge. The present findings therefore confirm that explicit sequence knowledge involves both spatial and verbal sequence representations (Verwey & Dronkers, 2019).

Despite the considerable variation of awareness amongst our participants we found no significant correlations between awareness and the size of the Simon effect. This confirms that even fully aware participants continued processing the key-specific stimuli. In fact, while aware participants were reported to ignore stimuli with 8-element binary responses in the serial RT task (Koch, 2007; Tubau & López-Moliner, 2004), we did not expect awareness in the DSP task to affect the Simon effect. The reason was that, compared with the serial RT task, in the DSP task it is difficult to disengage attention from the stimulus display area because the DSP task always requires identification of the first stimulus (as confirmed by the slowing of R_5 by incorrect letters in the 1-Placeholder condition). Also, the high execution rates in DSP sequences make it unlikely that participants would rely much on their explicit sequence knowledge (Verwey, 2015; Verwey & Wright, 2014).

5. Conclusions

The present experiments demonstrate that despite the development of strong sequence representations in discrete keying sequences (a) display of key-specific stimuli continues to attract visuospatial attention and to prime the response at the corresponding location. Given the automaticity of attention attraction and response priming, and the stability of the present Simon effect across practice, it is not likely that this will change with more practice than in the present experiments. (b) The relatively large Simon effect with the slow concatenation response in Experiment 2 is in line with the assumption of motor sequence learning models that motor sequencing skill involves a race between different systems to trigger each next response. (c) The reducing benefit of displaying letters over X's in Experiment 2 towards the end of each segment supports the notion that activation accumulates within the (central-symbolic and/or motor chunk) representations of each segment. This implies that these sequence representations benefit later responses more than earlier ones. (d) Awareness of the practiced sequences varies considerably across participants and involves spatial and verbal sequence knowledge, but awareness does not contribute much to sequence execution. This can be attributed to the slow rate at which individual responses are extracted from explicit sequence representations. (e) The awareness differences between the two experiments suggest that the development of explicit sequence knowledge can be stimulated after a reasonable amount of practice by removing stimuli past the first (cf. Verwey, in press). Together, the present results suggest that practice of sequential motor skills will benefit from displaying element-specific stimuli that do not attract visuospatial attention, for example, because they are isoluminant (as in Verwey, in press) or are displayed at a single location (as in Experiment 2).

Compliance with ethical standards

Authors Willem B. Verwey, David L. Wright and Rob H. J. Van der Lubbe declare that they have no conflicts of interest. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

CRediT authorship contribution statement

Willem B. Verwey: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - original draft. **David L. Wright:** Writing - review & editing. **Rob H.J. Van der Lubbe:** Writing - review & editing.

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