The Role of Visual Attention when Executing a Motor Sequence Production Task

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Abstract

Previous motor sequence learning studies suggest that when sequence representations have developed, participants can choose to ignore stimuli indicating the individual sequence elements if those do not attract attention, but tend to use them when they are displayed. The present study aimed at creating a practice situation in which attention is not attracted by individual key-specific stimuli and participants are persuaded to ignore them. The question was whether this would increase independence of the key-specific stimuli and therewith improve motor sequence learning. To test this, two experiments were performed in which participants practiced two 4-keypress sequences by responding to key-specific stimuli with different features. The results show that ignoring key-specific stimuli strengthens skill learning and further suggest that participants prepared for identifying isoluminant stimuli, which reduced sequence learning relative to Experiment 2. Experiment 1 showed that key-specific stimuli continue to be used when they are isoluminant if the first stimulus forces them to use a slower processing mode in which attention is captured by isoluminant stimuli. Experiment 2 suggests that to allow participants to ignore guidance by the key-specific stimuli, the color of the first stimulus should differ from the following stimuli so that after practice, only the salient first stimulus would capture attention and participants would not use a slower processing mode to process the isoluminant following stimuli.

Keywords: Discrete sequence production task, keying sequences, sequence learning, visual attention, motor skill

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List of Abbreviations

AFM	Additive Factors Method
Com	compatible S-R mapping
C-SMB	Cognitive framework for Sequential Motor Behaviour
Dif	different luminance
DSP	discrete sequence production
Inc	incompatible S-R mapping
Iso	isoluminant
min	minutes
Mix	mixed luminance condition: S_1 different luminance, S_{234} isoluminant
ms	milliseconds
RT	reaction time
SEM	standard error of the mean
S-R	stimulus-response
SRT	serial reaction time

1. Introduction

The development of motor skills plays a crucial role in our lives. There are a variety of learned actions that we can perform nearly automatically, and that allow us to function in everyday life, such as lacing shoes and using a computer. When we learn a new action, we pay full attention to carrying it out. But after repeating it, the action becomes nearly automatic and we can concentrate on another action while performing the previously learned action skillfully. Learned actions can then also be combined in sequences yielding fixed movement patterns. Consequently, we can perform subtasks automatically, which enables skilled performance in complex task environments such as car driving or playing video games. So, the development of sequential movement skills is highly important and has been extensively studied over the last half-century (for reviews, see, e.g., Abrahamse, Jiménez, Verwey, & Clegg, 2010; Rosenbaum, 2010; Verwey, Shea, & Wright, 2015).

It is assumed that acquiring the skill to perform fixed movement patterns involves the development of various sequence representations in memory that affect different levels of information processing (e.g., Hikosaka et al., 1999; Shea, Panzer, & Kennedy, 2016; Verwey et al., 2015). Various experimental procedures have been used to investigate changes in serial movement skills over practice in the laboratory. These include sequential key pressing tasks like the serial reaction time (SRT) task by Nissen and Bullemer (1987), the NxM task (Hikosaka, Rand, Miyachi, & Miyashita, 1995; Rand, Hikosaka, Miyachi, Lu, & Miyashita, 1998), and the *discrete sequence production* (DSP) task by Verwey (1999). The latter procedure involves participants responding to fixed series of key-specific stimuli. The typical DSP task is described in detail in the next section. Whereas participants initially react to each successively presented stimulus, with practice, however, representations develop that according to models of motor sequence learning eliminate the need for key-specific stimuli (Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013; Verwey et al., 2015). This leads to participants usually being able to perform the two practiced sequences in response to just the first key-specific stimulus. However, there are reasons to assume that the use of key-specific stimuli may be mandatory if they are displayed, because a luminance change of the stimulus as compared to the background automatically attracts attention and because participants tend to use key-stimuli even after extensive practice if they are beneficial for sequence execution (Verwey, Wright, & van der Lubbe, 2020; Verwey, 2020; see section 1.2 “The contribution of key-specific stimuli”). The present study aimed at creating a practice situation in which attention is not attracted by individual key-specific stimuli. The question was whether, if successful, this would increase independence of the key-specific stimuli and therewith improve motor sequence learning.

1.1. Skill development in discrete keying sequences

Motor sequence learning refers to the acquisition of the skill to rapidly and accurately produce a sequence of movements with limited effort and/or attentional monitoring. Over the past 20 years, the DSP task developed by Verwey (2001) extensively contributed to understanding the execution of well-learned, discrete movement patterns. The DSP task is characterized by sequence elements that take only very little time to produce, namely key presses. Utilizing such fast and simple movements allows reaction times (RTs) to reflect the cognitive processes that may remain concealed with other sequential movement tasks (Rhodes, Bullock, Verwey, Averbeck, & Page, 2004). While performing the DSP task, participants typically respond to each of two short series of 6 or 7 key-specific stimuli by pressing the corresponding key. To eliminate finger-specific effects on responses at a particular sequential position, as reported by, e.g., Adam (2008) and Leuthold and Schröter (2011), fingers of individual participants are counterbalanced across sequential positions. Sequence control is then explored using the RTs of the resulting series of key presses. The DSP task starts off with a practice phase in which participants repeat each of the two sequences 500-1000 times to develop the building blocks of a motor skill. 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). To account for that, Verwey et al. (2015) developed the Cognitive framework for Sequential Motor Behaviour (C-SMB), with assumptions inspired by the Additive Factors Method (AFM; Sanders, 1990, 1998), the bottleneck model for the Psychological Refractory Period task (Pashler & Christian, 1994), and the Dual Processor Model (Abrahamse et al., 2013; Verwey, 2001). The C-SMB assumes processors at three processing levels, namely the perceptual processors, the central processor, and the motor processors (see Figure 1). Accordingly, sequence knowledge is represented in perceptual, central-symbolic, and motor representations. These representations develop at different rates and also differ in the amount of central-cognitive processing required for triggering the individual responses (Verwey et al., 2015). If a stimulus is presented, its features are processed by a perceptual processor that transmits its output to the central processor by loading a perceptual representation into short-term memory.

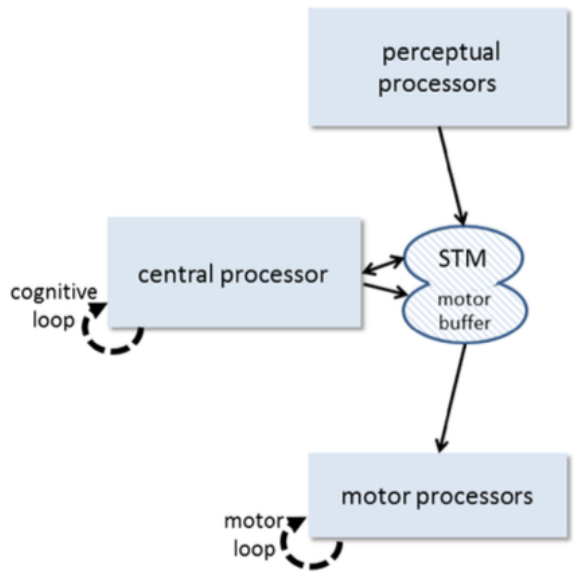

Figure 1: The processors at the perceptual, central and motor level assumed by the C-SMB. The depicted overlap between short-term memory (STM) and the motor buffer represents the storage of features with joint perceptual and motor significance. Adapted from "A cognitive framework for explaining serial processing and sequence execution strategies," by W. B. Verwey, C. H. Shea, and D. L. Wright, 2015, Psychonomic Bulletin & Review, 22(1), p.59.

Spatial and verbal sequence representations are developed during the first tens of trials, which require substantial cognitive processing. After hundreds of trials, participants develop a representation linking two or more key presses together into a so-called *motor chunk* that requires central-cognitive processing resources only for selecting and initiating the familiar motor sequences (Verwey, 1996), and that can be loaded into, and retrieved from, a so-called motor buffer. These sequence representations would involve motor parameters like activation patterns of agonist/antagonist muscles (Shea, Kovacs, & Panzer, 2011), musculoskeletal forces and dynamics (Krakauer, Ghilardi, & Ghez, 1999), joint angles (Criscimagna-Hemminger, Donchin, Gazzaniga, & Shadmehr, 2003), and/or posture-related representations (Rosenbaum et al., 2009). For these familiar sequences, the load on visual-working memory during preparation of the movements was found to be reduced, because segments of responses instead of individual responses can be kept in visual-working memory (De Kleine & Van der Lubbe, 2011). Motor chunks are assumed to represent a limited number of responses that can be selected and executed as if they are a single response in a control hierarchy (Miller, Galanter, & Pribram, 1960; Pew, 1966; Newell, & Rosenbloom, 1981; Verwey, 1996). As the so-called motor chunk sequence representations code the sequences motorically they can be executed faster than central-symbolic representations. During the DSP task, the central processor usually races with the motor processor to produce each next movement (Verwey et al., 2015).

1.2. The contribution of key-specific stimuli

Motor sequence learning models like C-SMB suggest that the contribution of the second and later key-specific stimuli reduces with practice. However, various earlier DSP studies did not show an independence from key-specific stimuli in that, even after extended practice, execution rate reduced when key-specific stimuli past the first were no longer displayed (Ruitenberg, Verwey, Schutter, & Abrahamse, 2014; Verwey, 1999; Verwey, Abrahamse, Ruitenberg, Jiménez, & De Kleine, 2011). As suggested by studies of visual search and response priming, it is possible that key-specific stimuli continue to contribute because participants cannot easily ignore them. Various visual search studies have shown that the luminance change that accompanies stimulus display automatically captures visuospatial attention (e.g., Belopolsky, Schreij, & Theeuwes, 2010; Jonides & Yantis, 1988; Theeuwes, 2010; Yantis & Jonides, 1984). Stimuli that produce automatic attention capture are often described as “salient” (Gaspelin & Luck, 2018). Accordingly, it is referred to as stimulus salience if features of objects or stimuli attract attention, i.e., bright colors, fast movements, or personal relevance (Yantis & Abrams, 2014). As a consequence, the contribution of such salient key-specific stimuli in sequencing tasks may not reduce, no matter the amount of practice. This contradicts the claim of motor sequence learning models.

To examine the role of key-specific stimuli in highly practice keying sequences, Verwey, Wright, and Van der Lubbe (2020) conducted a study to show whether learning sequential motor skills by responding to key-specific stimuli in the DSP task involves a reduction in reliance on these stimuli, as suggested by motor learning models, or whether key-stimuli continue to be used because salient key-specific stimuli capture visuospatial attention. Their experiments showed that even harmful stimuli, that did not correspond with the required response location, were processed. The results demonstrated that participants cannot ignore stimuli when these involve a luminance change that attracts attention, even when the sequences are highly practiced. Instead, Verwey (2020) showed that with isoluminant key-specific stimuli, that would not attract attention because they have the same luminance as the background, participants can control whether these isoluminant key-specific stimuli are being used. That is, participants seemed able to ignore these stimuli, for instance, because they know they have full sequence awareness (Tubau & López-Moliner, 2004) or because they realize that stimulus processing has little merit (Verwey, 2020). Still, they usually tend to continue using them when they are displayed, possibly because these stimuli are still beneficial and there is no reason to ignore them since processing them takes little cognitive effort. Accordingly, even though participants could ignore isoluminant key-stimuli, they may still use them when they seem beneficial for sequence execution. These findings led to the development of our present experiments.

1.3. **The present experiments**

The purpose of the present study was to explore whether participants develop stronger sequence representations in a DSP task if keying sequences are practiced when participants are persuaded to ignore guidance by the key-specific stimuli. This was supposed to be achieved with stimuli that involve incompatible S-R (stimulus-response) mappings that are harmful because they automatically trigger the wrong response (e.g., Kornblum, Hasbroucq, & Osman 1990). We further explored whether this would perhaps develop only with isoluminant stimuli because these do not capture attention and could therefore more easily be ignored.

Experiment 1

To test this, we chose a between-subjects experimental design to avoid learning and transfer across conditions. Further, knowledge of the test conditions could have biased behavior during practice. Therefore, the first experiment involved four groups. The first group (called *IsoInc*) practiced two keying sequences with isoluminant key-specific stimuli that were presented in locations incompatible with the response location. The second group (*DifInc*) also practiced with spatially incompatible S-R mappings, but the key-stimuli had a different luminance than the background. The third group (*IsoCom*) practiced with isoluminant key-specific stimuli that were presented at compatible S-R locations. Finally, the fourth group (*DifCom*) practiced with key-stimuli that had a different luminance and involved compatible S-R locations. We hypothesized that the combination of isoluminant stimuli and incompatible S-R locations in the IsoInc group persuades participants to ignore the key-specific stimuli that follow the first stimulus as soon as possible, and that this would boost development of the sequencing skill. In the case of the DifInc group, it was expected that they cannot ignore stimuli and do not learn to produce the sequences without stimuli. Moreover, if S-R mappings are compatible (in IsoCom and DifCom), participants continue using the key-stimuli because these are always beneficial.

For the first experiment, we decided to use 4-key sequences that do not involve concatenation of segments as occurs in 6- or 7-key sequences. This is due to the limited capacity of the motor buffer that can only contain 3-5 movements at a time (Verwey & Eikelboom, 2003; Verwey, Lammens, & van Honk, 2002). The execution of longer sequences requires concatenating successive subsequences, and consequently more stimulus processing (Acuna et al., 2014; Wymbs, Bassett, Mucha, Porter, & Grafton, 2012; Verwey et al., 2015) that might disrupt independence from the key-specific stimuli.

Applying the AFM to our experiment, an interaction between our two independent variables would imply that they concern the same processing stage, although according to findings with choice RT tasks the AFM posits that S-R compatibility and Luminance (Signal contrast) involve different processing stages (for an overview, see Sanders, 1990). This is also what we predicted for R_1. However, if after processing S_1 and selecting the appropriate sequence representation participants stop using the perceptual processing stages with incompatible S-R mappings (in IsoInc), then this may either slow R_{234} (because S_{234} are no longer used and sequence representations are not fast yet) or fasten R_{234} (because sequence representations eventually induce fast execution and S_{234} does not contribute much anyway because they are incompatible). In either case, an interaction would occur between S-R compatibility and Luminance for R_{234} (and not in R_1). This would not fit with the implications of the AFM that were derived from choice RT tasks. If, however, S_{234} continue to be used once S_1 is processed, R_{234} behave like R_1 and S-R compatibility and Luminance should be additive for R_1 as well as for R_{234}, as predicted by the AFM. To test whether reduced reliance on stimuli is indeed associated with improved learning in the IsoInc group we explored whether in that group performance would be better in a Single Stimulus condition where only the first key-stimulus of each sequence is presented and the participants have to complete the sequences without the help of further stimuli. With this test condition we explicitly tested which participants still used S_{234} during practice and would therefore perform worse in the Single Stimulus condition. We predicted that not displaying S_{234} would have the smallest effect on the IsoInc group, since they should be used to not using them.

In contrast, the skill to respond to stimuli was expected to be better in the DifCom and IsoCom groups because for these participants sequence learning would involve more responding to stimuli than for incompatible S-R locations (cf. Logan, 1988). Therefore, practicing with compatible S-R mappings would result in faster RTs in a Random Sequence test condition.

Moreover, we wanted to examine whether the ability to suppress attention attraction towards the stimulus is a skill that participants can eventually learn under certain conditions. It was hypothesized that while practicing with different luminant stimuli in incompatible S-R mappings (in DifInc), participants would have to actively suppress their attention to the location and would therefore learn to suppress the automated tendency to respond to that stimuli. Consequently, the DifInc group could show faster RTs in a Random Distractor test condition where two placeholders are filled each time and participants have to respond to the isoluminant stimuli and ignore the attention attracting color with a different luminance.

2. Methods

2.1. Participants

Forty-eight Bachelor and Master students (age range 18-28 years, mean age 23, 26 females, 26 Bachelor students) took part in Experiment 1. Thirty-two of them volunteered while sixteen received course credits for participation. As there was no data from a similar experiment available and consequently the expected effect size and other assumptions were difficult to estimate from earlier studies, a power analysis could not be reliably conducted. Therefore, a fixed number of 12 participants per group was chosen to attain a fully counterbalanced study design. Twelve participants per group is typical in DSP studies. The participants were randomly allocated to one of the four groups. The study had been approved by the ethics committee of the Faculty of Behavioral Sciences of the University of Twente. All participants provided written informed consent.

2.2. Apparatus

Stimulus presentation, timing, and data collection of Experiment 1 were achieved using the E-prime© 2.0 experimental software package on a standard Windows 10 PC. Instructions and stimuli were presented on a 25-inch AOC G2460PF LCD Monitor running at 1920 by 1080 pixel resolution in 24 bit color and a refresh rate of 144 Hz. Participants used four adjacent keys of a standard QWERTY PS2 keyboard (Logitech Deluxe 250 Keyboard), to react to the stimuli. We used a PS2 instead of a more common USB keyboard to allow more accurate RT measurement. Low level EPrime script in combination with the 144 Hz monitor and the PS2 keyboard allowed ms RT accuracy. During the experiment, unnecessary programs and Windows services were shut down to improve RT measurement accuracy. The room in which the participant performed the experiment was dimly lit with daylight and was equipped with a video camera for monitoring purposes. The viewing distance was approximately 50 cm, but this was not strictly controlled.

2.3. **Task**

The DSP task started by having the participants rest their left index and middle fingers on the C and V keys and their right index and middle fingers on the B and N keys. Four 2.7 × 2.7 cm square placeholders were presented horizontally in the center of the computer screen against a gray background. The placeholders consisted of black lines with the same gray background filling as default. Between each of the four placeholders, there was a 2.7 cm gap. Each key-specific stimulus, indicating that the corresponding key is to be pressed, consisted of a color change of the default gray filling of the placeholder (see Figure 2). During the practice phase, for the IsoInc group and the IsoComp group, the placeholder was filled with a blue-green (RGB values 0/83/83) that had the same luminance as the gray background (47 Lux, as tested with a UNI-T UT383 Mini Light Meter). For the DifInc group and the DifCom group, the placeholder changed to a yellow filling with a luminance of 126 Lux (RGB values 200/200/0) that differed of that from the background (RGB values 80/80/80).

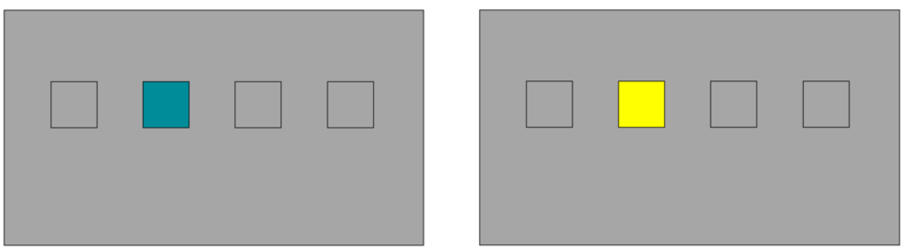

Figure 2: Color change of isoluminant and different luminance stimuli (left vs. right frame, respectively).

When the correct key had been pressed, the placeholder changed back to the gray background color and the ensuing key-stimulus was presented immediately after the onset of the previous keypress. This resulted in a response-stimulus interval (RSI) of 0 ms. For the two incompatible S-R groups (IsoInc and DifInc), the correct response key corresponded to the spatially opposite key-stimulus (see Figure 3). For the two compatible S-R groups (IsoCom and DifCom), the correct response key spatially matched the stimulus.

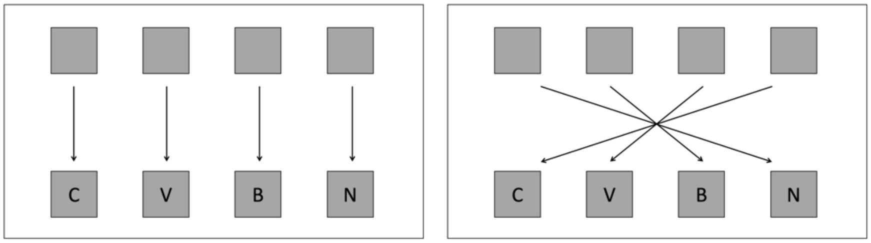

Figure 3: Compatible vs. incompatible S-R mapping

After the last response of a sequence, the display was cleared for 2000 ms and the empty placeholders were shown again for 500 ms. Then, the first key-stimulus of the next series was presented. Pressing the wrong key resulted in the message "error, try again …" in red and clearly readable letters above the placeholders for 1500 ms, after which the sequence was broken off and the display was cleared. When a participant did not give a response within 5000 ms, the message "no response try again …" was displayed over the placeholders for 1500 ms, and the sequence was broken off.

The two 4-key sequences of each participant were selected from a set of four counterbalanced sequences: NVBC, BCVN, VNCB, and CBNV. This counterbalancing involved rotating between the four keys (N→B→V→C→ etc.), so that, across participants, each finger occurred equally often at each particular sequential position.

2.4. **The practice phase**

The DSP task involved five practice blocks that consisted of two 60-trial subblocks separated by a break of 20 seconds. The two sequences were always presented in random order. With 60 trials per sequence per block, this yielded a total of 300 practice trials per sequence. This is more than half of the typical number of about 500 practice trials in the regular DSP studies for 6- to 7-key sequences and was assumed to be sufficient for learning 4-key sequences. Indeed, this number of practice trials was confirmed to be sufficient to learn the sequences in a pretest with two participants, since RTs did not further decrease substantially in the last practice block and they also correctly reproduced the practiced sequences in the following Single Stimulus condition. Each practice block was followed by a 3-min break.

2.5. **The test phase**

The ensuing test phase consisted of three test subblocks, each including 60 sequences. For all participants, key-stimuli were presented in a compatible S-R mapping. The first test block represented a Single Stimulus condition, as only the first stimulus of each sequence was displayed and the participants were requested to complete the sequences without further key-stimuli and included 30 trials with each of the 2 practiced sequences in a random order. The single stimulus had the same yellow color (126 Lux) as during practice for the Dif groups, yielding in Different Luminant stimuli (see Figure 2b) for all participants.

To test the skill to respond to stimuli, the second test block was a random sequence condition, in which stimuli were presented randomly without a specific order, thus yielding 60 different sequences per block. Again, the same yellow stimuli with a different luminance (126 Lux) were used.

Finally, to test the ability to suppress attention attraction towards the stimulus, the third test block was a random sequence condition in which a distractor stimulus was presented in addition to an imperative key-stimulus. The imperative stimuli were isoluminant to the background (47 Lux), whereas the distractor had a luminance of 126 Lux. To avoid any benefits for certain practice groups, in this test condition both the isoluminant stimuli and the distractor had different colors than during the practice phase: The isoluminant imperative stimuli were filled with dark pink (RGB values 108/19/108) and the distractors with a bright green color (RGB values 0/255/0) (see Figure 4). The order of the three test blocks was counterbalanced across participants, and these were separated by a break of 20 seconds followed by a brief instruction for the oncoming task.

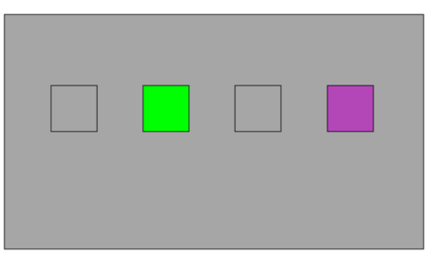

Figure 4: Random distractor test condition with two stimuli.

2.6. **Awareness task**

The awareness of the two sequences was assessed with a computerized awareness task (Verwey & Dronkers, 2019). It consisted of two different awareness tests that were administered in a counterbalanced order across participants. In the *Spatial test*, four empty 2.5 × 2.5 cm placeholders were displayed in a horizontal row, like with the previous keying task itself. Between each of the four placeholders, there was a 5.5 cm gap. While the keyboard was covered, participants were asked to use the mouse to click the placeholders in the same order as the keys had been pressed in each of the two practiced keying sequences. As response feedback, each mouse click was followed by a brief green flash of the selected placeholder. With this test, explicit spatial sequence knowledge was examined, by testing explicit knowledge of the locations of the successively pressed keys.

In the *Verbal Response test*, the four placeholders were displayed in a rhombus configuration, and each placeholder contained a letter of the response keys the participants had been pressing. The placeholder at the top contained the letter N, the one at the bottom contained the letter B, and the ones at the left and right contained V and C, respectively. The placeholders were located at a distance of 10 cm (from bottom to top) and 14 cm (from left to right) and the angles between the connecting lines were 90°. Participants were required to click the placeholders in the order of the response letters for each of the two practiced sequences. Again, each mouse click was followed by a brief green flash of the selected placeholder as response feedback. This test examined explicit verbal sequence knowledge in terms of the letters on the four response keys. After that, participants were asked to indicate for each of the two pointing tasks, how they did decide which sequences they just carried out, and how confident they are about the sequences they indicated. Eventually, these awareness data were captured but not analyzed.

2.7. **Procedure**

The experiment was conducted at the BMS Lab of the University of Twente. As the data were captured during the COVID-19 pandemic, we had to take several precautions. These included only allowing one participant in the Lab at a time to be able to keep sufficient distance, a short survey about the participants' health prior to entering the Lab, disinfection of the apparatus after each participant, and collecting contact details which were stored separately from the experiment data and only served to inform participants in case of a potential infection in the building.

Before the start of the experiment, participants filled out an informed consent form and received written instructions on the task to be performed. Additionally, during the experiment, detailed instructions were provided on the computer display. Because of the color change of the stimuli in two conditions, all participants were tested for color blindness using a simplified version of the Ishihara test (e.g., Birch, 1997). Before the start of the experiment, participants were told that the whole experiment would last about 1.5 hours. They were instructed to respond as fast as possible when performing the tasks while not making too many errors (mean RTs and error rates were displayed at end of each subblock and should not exceed 8 %). Participants started with the practice phase and carried out the five practice blocks. After completing the 5th practice block and a break of 3 min, the test phase consisting of three subblocks started. Finally, after the last test subblock, the participants carried out the awareness task.

3. Results

Mixed analyses of variance (ANOVAs) were used to analyze RTs and the arcsine transformed error proportions of the practice and test blocks, respectively. If the sphericity assumption was violated a Greenhouse-Geisser transformation was used to correct the degrees of freedom of the F-tests. Given the high number of trials and experience from earlier studies outlier exclusion was not necessary. Effect sizes were reported as partial eta squared (η^2_p).

3.1. Practice phase

To test the hypotheses regarding the development of sequence representations during practice, two mixed ANOVAs were performed. One for the first response (R_1) and one for the following responses (R_{234}).

First, mean response times of errorless sequences per Participant and Block for R_1 were analyzed using a 2 (Luminance: Iso vs. Dif) × 2 (S-R mapping: Com vs. Inc) × 5 (Block) mixed ANOVA with luminance condition and S-R mapping as between-subjects variables and Block as a within-subjects variable. It showed the usual effect of Block, $F(2.13, 93.83) = 26.72$, $p < .001$, $\eta_p^2 = .38$, indicating that RT reduced across successive blocks. Regarding the between-subjects variables, S-R mapping showed a main effect, $F(1, 44) = 27.83$, $p < .001$, $\eta_p^2 = .39$, showing that the two Com groups were faster than the Inc groups (400 ms vs. 517 ms; see Figure 5a). Moreover, the Dif groups were faster than the Iso groups (427 vs. 490 ms), $F(1, 44) = 8.02$, $p = .007$, $\eta_p^2 = .15$ (Figure 5b). There was no significant S-R mapping × Luminance interaction, $F(1, 44) = .24$, $p = .63$. Accordingly, S-R mapping and Luminance had the expected additive effects and this did not change across practice. There was an interaction between S-R mapping and Block, $F(2.13, 93.83) = 4.80$, $p = .009$, $\eta_p^2 = .10$, implying that the disadvantage of the incompatible group reduced across blocks (see Figure 5a).

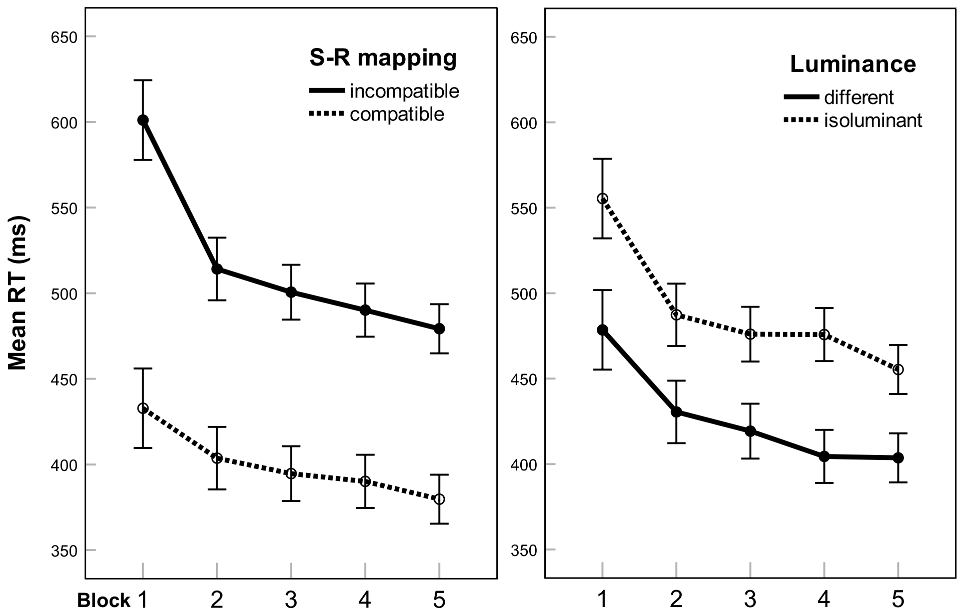

Figure 5: Mean RTs for R_1 in the practice phase as a function of practice block and a) S-R mapping and b) luminance condition. Error bars indicate the standard error of the mean (SEM).

Next, we analyzed the mean response times of errorless sequences per Participant and Block for R_{234} using a 2 (Luminance: Iso vs. Dif) × 2 (S-R mapping: Com vs. Inc) × 5 (Block) × 3 (Key) mixed ANOVA with luminance condition and S-R mapping as between-subjects variables and Block and Key as within-subjects variables. It again showed a main effect of Block, $F(1.49, 65.60) = 267.18$, $p < .001$, $\eta_p^2 = .86$, and of Key, $F(2, 88) = 33.54$, $p < .001$, $\eta_p^2 = .43$, indicating that RT reduced across successive blocks and with successive keys. Furthermore, Block interacted with Key, $F(2.67, 117.62) = 15.61$, $p < .001$, $\eta_p^2 = 0.26$, indicating that these learning effects across blocks were element specific. Also, the Com groups were again faster than the Inc groups (150 ms vs. 263 ms), $F(1, 44) = 25.93$, $p < .001$, $\eta_p^2 = .37$. Moreover, there was an interaction between S-R mapping and Block, $F(1.49, 65.60) = 41.87$, $p < .001$, $\eta_p^2 = .49$, an S-R mapping × Key interaction, $F(2, 88) = 7.67$, $p = .001$, $\eta_p^2 = .15$, and an S-R mapping × Block × Key interaction, $F(2.67, 117.62) = 3.29$, $p = .028$, $\eta_p^2 = .07$, implying that improvement across practice blocks for R_{234} differed for the Inc and Dif groups (see Figure 6). However, Luminance did not have an effect on R_{234}, $F(1, 44) = 2.80$, $p = .10$, and there was no Luminance × S-R mapping interaction, $F(1, 44) = .54$, $p = .47$, and also no Luminance × S-R mapping × Block interaction, $F(1.49, 65.60) = .31$, $p = .69$.

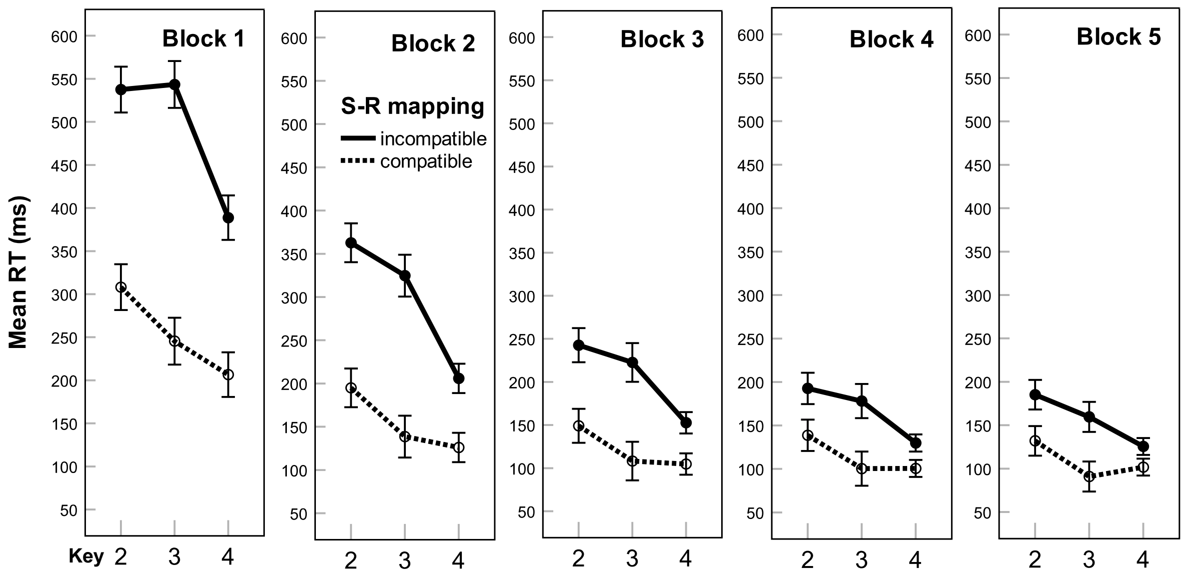

Figure 6: Mean RTs for R_{234} in the practice phase as a function of S-R mapping, Key and practice block. Error bars indicate the SEM.

To analyze the arcsine transformed error proportions (Winer, Brown, & Michels, 1991) obtained in the practice phase, we used a mixed ANOVA with a 2 (Luminance: Iso vs. Dif) × 2 (S-R mapping: Com vs. Inc) × 5 (Block) × 4 (Key) design per participant, block and key position. It showed a main effect of Block, $F(3.19, 140.45) = 4.99$, $p = .002$, $\eta_p^2 = .10$, whereby contrasts revealed that participants made significantly more errors in the first Block compared to the other blocks (2.4 % vs. 1.8 % – 1.9 % per key). Moreover, error rate increased from Key positions 1 to 3 (1.5 %, 2.4 %, 2.6 %, resp.), but was lowest for R_4 (1.2 %), $F(2.36, 103.63) = 17.78$, $p < .001$, $\eta_p^2 = .29$.

The incompatible S-R mapping led to a higher error rate than the compatible mapping, (2.8 % vs. 1.1 % per key, resp.), $F(1, 44) = 24.92$, $p < .001$, $\eta_p^2 = .36$, whereas there was no significant difference in error rates between the two luminance conditions (see Figure 7b). As indicated by the Block × S-R mapping interaction, the error rates of the practice blocks differed according to whether the S-R mapping was compatible or incompatible, $F(3.19, 140.45) = 3.75$, $p = .011$, $\eta_p^2 = .08$ (see Figure 7a).

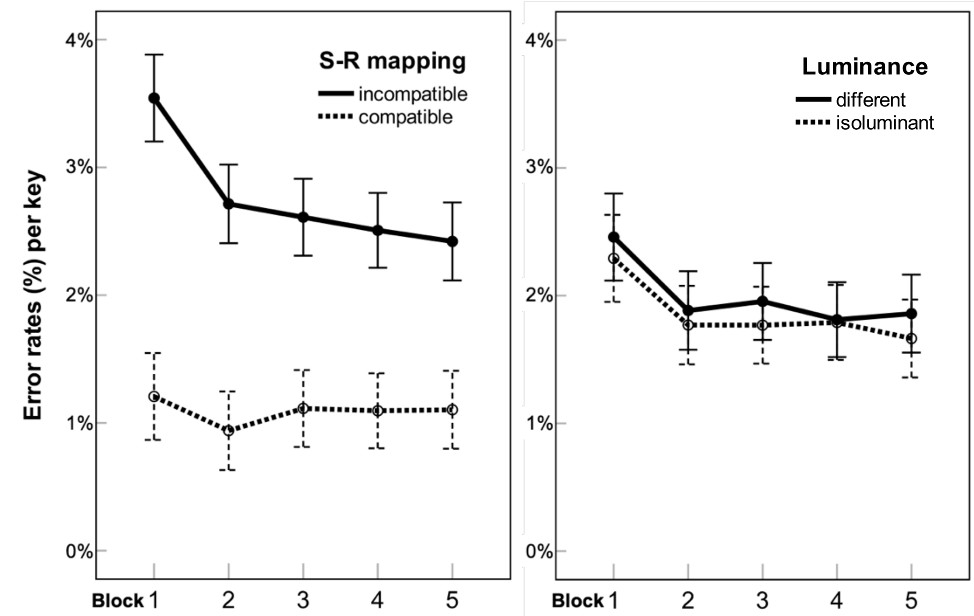

Figure 7: Error rates in the practice phase across all four keys as a function of practice block and a) S-R mapping and b) luminance condition. Error bars indicate the SEM.

3.2. **Test phase**

To test our hypotheses that 1) participants would better learn keying sequences with isoluminant key-specific stimuli in combination with incompatible S-R mappings, 2) practice with compatible S-R mappings would yield stronger S-R learning, and 3) participants who practice with incompatible S-R mappings might learn to suppress attention attraction by different luminance stimuli, two mixed ANOVAs were performed. One for the Single Stimulus condition and one for the similar Random Sequence – and Random Distractor conditions.

First, the mean RTs of errorless sequences per participant and key position obtained in the Single Stimulus test condition – which was identical for all participants - were analyzed with a 2 (Luminance condition during practice: Iso vs. Dif) × 2 (S-R mapping during practice: Com vs. Inc) × 4 (Key) mixed ANOVA with Luminance and S-R mapping as between-subjects variables. This ANOVA showed a significant main effect for Key position, $F(1.80, 79.35) = 84.84$, $p < .001$, $\eta_p^2 = .66$, indicating that RT decreased along sequential key positions. Moreover, prior practice with compatible S-R mappings led to shorter RTs in the Single Stimulus condition than practice with the incompatible S-R mapping, $F(1, 44) =$

8.92, $p = .005$, $\eta_p^2 = .17$ (see Figure 8). Furthermore, there was a significant Key × S-R mapping interaction, $F(1.80, 79.35) = 8.92$, $p = .035$, $\eta_p^2 = .08$, indicating that the differences between RTs of compatible and incompatible S-R mappings reduced with key position. The effect of Luminance suggested that practice with isoluminant stimuli led to slower responses (336 ms vs. 260 ms), $F(1, 44) = 3.80$, $p = .058$, $\eta_p^2 = .08$.

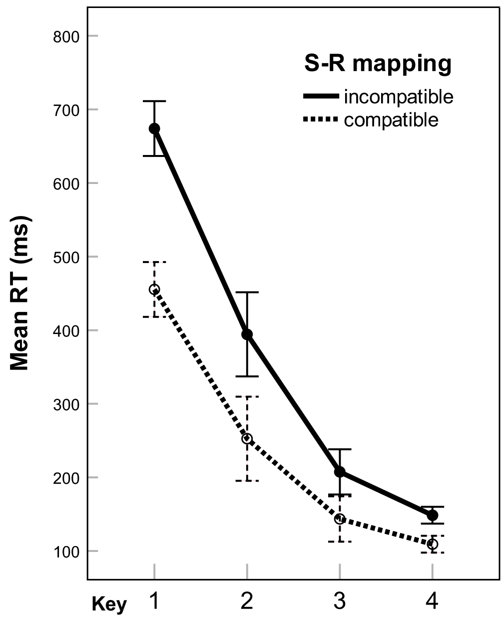

Figure 8: The effect of S-R mapping during practice on the mean RTs in the Single Stimulus condition. Error bars indicate the SEM.

Next, mean RTs of errorless sequences per participant and key position obtained in the Random Sequence and Random Distractor conditions were analyzed with a 2 (Luminance condition during practice: Iso vs. Dif) × 2 (S-R mapping during practice: Com vs. Inc) × 2 (Condition: Random Sequence vs. Random Distractor) × 4 (Key) mixed ANOVA. It showed that RTs were significantly slower in the Random Distractor condition than in the Random Sequence condition (495 ms vs. 418 ms), $F(1, 44) = 156.00$, $p < .001$, $\eta_p^2 = .78$. Again, there was a significant main effect for Key position, $F(1.74, 76.48) = 27.00$, $p < .001$, $\eta_p^2 = .38$, indicating that RTs varied across key positions (see Figure 9). Moreover, prior practice with different luminance stimuli led to faster RTs across both test conditions (434 ms vs. 478 ms), $F(1, 44) = 7.56$, $p = .009$, $\eta_p^2 = .15$, and this was significant also for just the Random condition (398 ms vs. 437 ms),

$F(1, 44) = 7.99$, $p = .007$, $\eta_p^2 = .15$, and just the Random Distractor condition (470 ms vs. 520), $F(1, 44) = 6.10$, $p = .017$, $\eta_p^2 = .12$.

Two interactions almost reached significance, namely the Key × S-R mapping interaction, $F(1.74, 76.48) = 2.87$, $p = .070$, $\eta_p^2 = .06$, and the Condition × Key × S-R mapping interaction, $F(3, 132) = 2.50$, $p = .06$, $\eta_p^2 = .05$. Those marginally significant interactions suggested that depending on the key position, there were some differences between the Com and Inc groups in the Random Sequence condition (see Figure 9b).

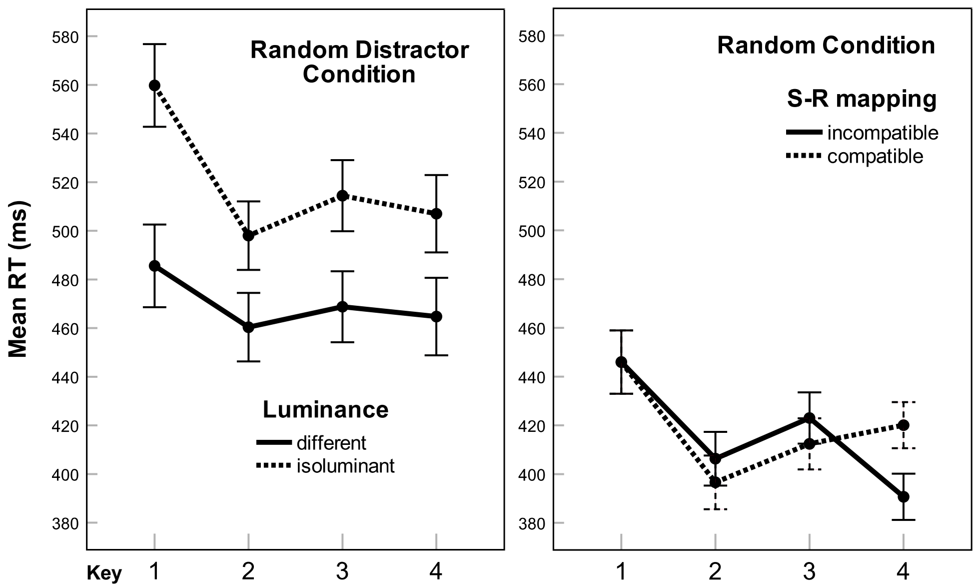

Figure 9: a) The effect of luminance during practice on mean RTs in the Random Distractor condition b) The effect of S-R mapping during practice on mean RTs in the Random Sequence condition. Error bars indicate the SEM.

Arcsine transformed error proportions per participant, test condition and key position obtained in the test phase were analyzed with a 2 (luminance condition during practice: Iso vs. Dif) × 2 (S-R mapping during practice: Com vs. Inc) × 3 (Test Condition: Random, Random Distractor, Single Stimulus) × 4 (Key) mixed ANOVA. Again, luminance condition and S-R mapping served as between-subjects variables.

The ANOVA showed main effects of Test Condition, $F(1.31, 57.51) = 12.83$, $p < .001$, $\eta_p^2 = .23$, and Key, $F(3, 132) = 12.46$, $p < .001$, $\eta_p^2 = .22$, implying that more errors were made in the Single Stimulus condition than in the Random and Random Distractor condition (6.9 % vs. 3.4 % and 2.9 % per key, resp.)

and that error rate varied across key positions (2.1 %, 6.1 %, 5.1 %, 4.3 %, resp.). Moreover, error rates were higher for the incompatible S-R mapping group than the compatible group (5.5 % vs. 3.3 % per key, resp.), $F(1, 44) = 7.47$, $p = .009$, $\eta_p^2 = .15$. There was no significant difference in error rates between the two Luminance conditions. The interactions between Condition × S-R mapping, $F(1.31, 57.51) = 9.68$, $p = .001$, $\eta_p^2 = .18$, Condition × Key, $F(4.25, 187.02) = 22.55$, $p < .001$, $\eta_p^2 = .34$, and Condition × Key × S-R mapping, $F(4.25, 187.02) = 4.50$, $p = .001$, $\eta_p^2 = .09$, showed that the error rates between compatible and incompatible practice differed most in the Single Stimulus condition (3.9 % vs. 9.9 % per key, resp.) and only little in the other two test conditions and that in the Single Stimulus condition R_2 caused the highest error rates, whereas in the other two test conditions error rates peaked at R_4.

4. Discussion

The main questions in Experiment 1 were whether participants better learn keying sequences with isoluminant key-specific stimuli in combination with incompatible S-R mappings because they rapidly start ignoring key-specific stimuli, whether practice with compatible S-R mappings yields stronger S-R learning, and whether participants who practiced with incompatible S-R mappings have learned to suppress attention attraction by different luminance stimuli. To examine this, four groups of participants practiced a DSP task with either different or the same luminance of the key-specific stimuli and with either compatible or incompatible S-R compatibility.

The significant main effects of S-R mapping and luminance condition during practice showed that both manipulations indeed had an effect on RT. In general, both incompatible S-R mappings and isoluminant stimuli led to slower RTs. Although we expected an interaction of Luminance and S-R compatibility for R_2, R_3, and R_4 in the practice phase, we only found additive effects of these variables.

The analysis of the practice phase revealed that both incompatible groups improved more than those with compatible S-R mappings, for R_1 (see Figure 5a), as well as for R_{234} (see Figure 6). This finding showed that participants either 1) gradually learned to ignore incompatible stimuli because they developed sequence representations (as predicted for IsoInc), or 2) that they had gradually learned to deal with incompatible mappings by developing new S-R associations and better suppress priming of the compatible responses by stimulus display.

As isoluminant stimuli led to longer RTs during practice, the lower signal contrast had apparently slowed perceptual processing of the isoluminant stimuli (Sanders, 1990). However, there was no interaction between Luminance and S-R compatibility for R_{234} as we predicted when key-specific stimuli would be ignored. Further, luminance did not interact with Key and Block. Accordingly, during practice, S_{234} continued to be used irrespective of practice and S-R compatibility. However, we found that in Block 5, the compatibility effect was much smaller for R_{234} (~30-50 ms) than for R_1 (~100 ms). This difference suggests that sequence learning did compensate for the incompatible S-R mapping to some extent, which is precisely what the race hypothesis of C-SMB predicts when stimuli continue to be used while sequences are learned (Verwey et al., 2015). So, participants did not learn to ignore key-specific stimuli as we expected but did use their sequence representations. So, there is no evidence for participants ignoring stimuli when practicing incompatible stimuli, even when they were isoluminant. As the use of S_{234} was similar in all conditions participants seem not to have learned to ignore stimuli in the incompatible conditions as we hypothesized.

This suggests that sequence learning should eventually be similar in all four groups. This is precisely what the Single Stimulus condition showed, no advantage for the IsoInc group over the other 3 groups. The goal of using an incompatible S-R mapping during practice was to make the key-stimuli harmful for the participants, therefore giving them a reason to ignore them and develop sequence representations independent from those key-specific stimuli. However, although the Inc groups had reason to ignore the following harmful stimuli, they apparently did not do that, no matter whether stimuli were iso-luminant or had another luminance than the background. We account for this finding by the notion that, as participants always needed to process S_1 because it indicated which of the two sequences they had to produce, the first stimulus was set to always capture attention, no matter if it was isoluminant or not. Therefore, participants may not have been able to intentionally ignore the ensuing key-stimuli, as suggested by Verwey (2020), because they first had to identify S_1. Indeed Lambert, Wells, and Kean (2003) conducted various experiments to study the effects of peripheral cues on visual orienting under different conditions and found that both luminant and isoluminant cues can be set to capture attention if the task requires it. These findings suggest that the participants in Experiment 1 prepared a processing mode in which attention is captured by isoluminant stimuli to identify S_1. Once having identified S_1, the cognitive load of executing a sequence may then have prevented them from changing to the mode in which attention is not captured by isoluminant stimuli.

Interestingly, participants who had practiced with incompatible S-R mappings were slower in the Single Stimulus condition than those who had practiced with compatible S-R mappings, instead of faster. This may have been caused by 1) a reduced availability of cognitive resources during practice due to increased demands at the response selection stage, or 2) by reduced motor chunk learning in the incompatible practice conditions because of the longer R-R intervals during practice (Verwey & Dronkers, 2019). Notice here that limited availability of cognitive resources would reduce the development of central-symbolic representations and not of motor chunks. If so, explicit sequence knowledge may be less in the incompatible groups too. 3) Slowed learning in the incompatible S-R mapping groups may have also been caused by these participants having learned to execute sequences more slowly in order to take the incompatible stimuli into account (Wong, Goldsmith, Forrence, Haith, & Krakauer, 2017).

Still, the fact that execution rate increased towards the end of the sequence in the Single Stimulus condition, especially for the incompatible S-R mapping group (see Figure 8), suggests that all groups did develop sequence representations in which activation accumulated across successive responses (Verwey et al., 2015). These results, too, show no differences between the IsoInc and the other groups that could have supported enhanced sequence learning.

Our second prediction was that practice in the compatible groups would result in faster random sequence performance due to improved S-R learning (Logan, 1988). However, the results in the Random test condition showed no benefit for the groups that practiced with compatible S-R mappings (Figure 9b). This shows that the incompatible mapping groups were just as efficient using compatible S-R mappings as the compatible participants, and that practice with compatible mappings did not facilitate use of this natural mappings. Instead, participants who had practiced with isoluminant stimuli again showed slower RTs in the Random condition. This is in line with the notion that Iso participants had developed a strategy of taking more time for identifying stimuli (Wong et al., 2017), and that this persisted in each Random condition, without or without distractor. In the current setup, it is possible also that the Dif participants had a familiarity advantage in that they were already used to reacting to the yellow attention attracting stimuli during practice. In contrast, the yellow stimuli were new to the Iso participants, which might have yielded slower responses.

Finally, the prediction was not supported that DifInc participants are better able to suppress an attention attracting stimulus than other participants. S-R compatibility during practice did not have any effect on RTs in the random conditions, and the results only show that isoluminant practice yielded considerably slower responding to different luminant stimuli of another color. This finding suggests that isoluminant practice yields a tendency to take more time to identify a stimulus, irrespective of the actual luminance of the stimulus (IsoLum participants did not have fewer errors). There indeed is some evidence indicating that participants prepare the time they will use to process a stimulus, and then continue after that time with the best identified stimulus. According to Wong et al. (2017), RT does not strictly reflect the time needed to complete the computations required for preparing responses but may instead be selected habitually according to prior experience. So, when a previously performed task required a specific RT to support task success, this biased the RTs in future tasks of their experiments. The same might have occurred in the present study in that experience with isoluminant stimuli, which take longer to identify, biased and prolonged the RT during the test condition. So, no matter how they practiced, none of the four groups was better able to ignore the distractor, and there was no learning effect.

To summarize the findings of Experiment 1, we discovered that S_{234} continued to be used irrespective of practice, luminance, and S-R compatibility. Indeed, we found that all groups developed sequence representations, and as a consequence sequence learning was not better for IsoInc participants and was in fact reduced for both Inc groups. We discussed several explanations that would account for this finding, but it is unclear which of them actually may have caused the effect. The luminance manipulation was aimed at enabling participants to ignore the isoluminant S_{234} since recent findings suggest that stimuli with a different luminance cannot be ignored (Verwey et al., 2020), whereas participants seem able to ignore isoluminant stimuli (Verwey, 2020). However, the results of the practice phase showed that participants continued to use the key-specific stimuli, even when they were isoluminant, and indeed sequence learning was not better in the IsoInc group. There is evidence from several studies that salient stimuli naturally attempt to capture attention, but that capture can be avoided if the salient stimulus is suppressed before it captures attention (for a review, see, e.g., Gaspelin & Luck, 2018). Conversely, in the present experiment the need to process S_1 may have forced the Iso participants to use a different (slower) processing mode in which isoluminant stimuli capture attention too. After having identified the salient isoluminant S_1, they apparently did not switch back to normal processing mode and therefore S_{234} captured attention too. This did not allow them to start such an inhibition process as Gaspelin and Luck (2018) proposed and consequently S_{234} could not be ignored during practice. The finding that participants did not ignore the following key-stimuli also explains that there was no difference in S-R learning, and in the skill to suppress stimuli with a different luminance.

Experiment 2

Based on the results of Experiment 1, we developed a second experiment to test whether isoluminant participants had not been able to ignore S_{234} because they were always forced to identify the first stimulus and continued in this processing mode afterwards. To investigate this, in Experiment 2 the first stimulus of each sequence was always presented with a different luminance while the following stimuli (S_{234}) were isoluminant. As everything else was kept the same, this resulted in *MixInc* practice group that could be compared with the practice groups of Experiment 1. By doing so, we wanted to prevent attentional capture by the isoluminant stimuli because participants were not anymore required to process the first one to identify which of the two sequences they had to produce. Therefore, we predicted that the color change between S_1 and S_{234} would enable participants to suppress stimuli with this particular feature value of isoluminance and this would boost the development of sequencing skill still. So, we expected the new MixInc group to show increased independence of S_{234} and faster RT in the Single Stimulus Condition compared to the IsoInc group from Experiment 1. To enable a comparison between the new MixInc group and the IsoInc group from Experiment 1, Experiment 2 was exactly the same except for the color of the first stimulus during practice.

5. Methods

5.1. Participants

Twelve Bachelor and Master students (age range 18-24 years, mean age 21, 6 males, 10 Bachelor students) took part in Experiment 2. Ten of them received course credits for participation while two volunteered. Like in Experiment 1, a fixed number of 12 participants was chosen to attain a fully counterbalanced study design. Experiment 2 had been approved as an extension of the first study by the ethics committee of the Faculty of Behavioral Sciences of the University of Twente. All participants provided written informed consent.

5.2. **Apparatus**

Stimulus presentation, timing, apparatus, and data collection were as described with Experiment 1. Moreover, we created the same lighting and temperature conditions and conducted the experiment in the same room at the BMS Lab of the University of Twente.

5.3. **Task**

The DSP task had the same incompatible S-R mapping as IsoInc in Experiment 1. Again, each key-specific stimulus consisted of a color change of the default gray filling of the placeholder (see Figure 10). The only difference was that for the new MixInc group, during the practice phase, for each first stimulus the placeholder changed to a yellow filling with a luminance of 126 Lux (RGB values 200/200/0) that differed of that from the background (RGB values 80/80/80), whereas the following stimuli S_{234} were indicated by filling the placeholder with a blue-green (RGB values 0/83/83) that had the same luminance as the gray background (47 Lux; see Figure 10).

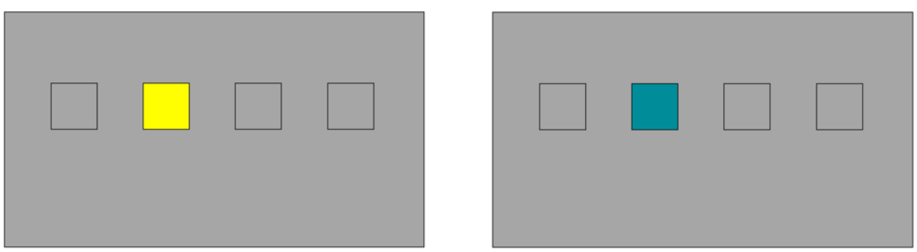

Figure 10: Color change of S_1 (yellow) and the following S_{234} (blue-green) during practice of Experiment 2 (MixInc practice condition).

Like in Experiment 1, the DSP task of Experiment 2 involved five practice blocks that consisted of two 60-trial subblocks separated by a break of 20 seconds. The two sequences were always presented in random order. With 60 trials per sequence per block, this yielded a total of 300 practice trials per sequence. Each practice block was followed by a 3-min break.

The ensuing test phase was precisely the same as in Experiment 1. Participants performed a Single Stimulus condition and a Random Sequence condition with yellow stimuli that had a different luminance as the background and a Random Distractor condition with green distractor stimuli and pink isoluminant key-stimuli. Again, the three test conditions were presented in a counterbalanced order. Each condition contained 60 trials and the test blocks were separated by a break of 20 seconds followed by a brief instruction for the oncoming task. Finally, participants performed the same computerized awareness task that consisted of the Spatial test and the Verbal Response test, administered in a counterbalanced order across participants.

5.4. **Procedure**

Due to the ongoing COVID-19 pandemic, we took the same precautions as during Experiment 1 to follow hygienic protocols. Before the start of the experiment, participants filled out an informed consent form, received the same written instructions on the task to be performed, and were tested for color blindness using a simplified version of the Ishihara test (e.g., Birch, 1997). After reading detailed instructions presented on the computer display, participants started with the practice phase and carried out the five practice blocks. After completing the 5th practice block and a break of 3 min, the test phase started. Finally, after the last test subblock, the participants carried out the awareness task. The duration of the experiment was again about 1.5 hours.

6. Results

Mixed analyses of variance (ANOVAs) were used to analyze RTs and the arcsine transformed error proportions of the new MixInc group and the IsoInc group from Experiment 1. Again, we analyzed the practice and test blocks, respectively.

6.1. Practice phase

Two mixed ANOVAs were performed. One for the first response (R_1) and one for the following responses (R_{234}). First, mean response times of errorless sequences per Participant and Block for R_1 were analyzed using a 2 (Luminance: Iso vs. Mix) × 5 (Block) mixed ANOVA with luminance condition as a between-subjects variable and Block as a within-subjects variable. It showed the usual effect of Block, $F(2.05, 45.09) = 13.05$, $p < .001$, $\eta_p^2 = .37$, indicating that RT reduced across successive blocks. Luminance did not have a significant effect on R_1 and there were no further interactions.

Next, we analyzed the mean response times of errorless sequences per Participant and Block for R_{234} using a 2 (Luminance: Iso vs. Mix) × 5 (Block) × 3 (Key) mixed ANOVA with luminance condition as a between-subjects variable and Block and Key as within-subjects variables. It again showed a main effect of Block, $F(1.47, 32.25) = 138.48$, $p < .001$, $\eta_p^2 = .86$, and of Key, $F(2, 44) = 22.27$, $p < .001$, $\eta_p^2 = .50$, indicating that RT reduced across successive blocks and with successive keys. Furthermore, Block interacted with Key, $F(2.79, 61.47) = 7.77$, $p < .001$, $\eta_p^2 = 0.26$, indicating that these learning effects across blocks were element-specific. However, there was no significant effect of Luminance across R_{234}, $F(1, 22) = .36$, $p = .417$, and no further interactions.

To analyze the arcsine transformed error proportions obtained in the practice phase, we used a mixed ANOVA with a 2 (Luminance: Iso vs. Mix) × 5 (Block) × 4 (Key) design per Participant, Block and Key position. It showed a main effect of Block, $F(4, 88) = 2.83$, $p = .029$, $\eta_p^2 = .11$, whereby contrasts revealed that participants made significantly more errors in the first Block compared to the other blocks (3.0 % vs. 2.1 % – 2.3 % per key), $F(1, 22) = 6.80$, $p = .016$, $\eta_p^2 = .24$. Moreover, error rate varied across Key positions and was highest for R_2 (3.1 %) and lowest for R_4 (1.4 %), $F(3, 66) = 8.31$, $p < .001$, $\eta_p^2 = .27$.

There was no significant difference in error rates between the two luminance conditions. As indicated by the Block × Key interaction, the error rates of the key positions varied in the different practice blocks, $F(3.19, 140.45) = 3.75$, $p = .011$, $\eta_p^2 = .08$.

6.2. **Test phase**

To test the hypotheses regarding the development of sequence representations, S-R learning, and stimulus suppression, again two mixed ANOVAs were performed. One for the Single Stimulus condition and one for the combination of the Random Sequence and the Random Distractor conditions.

First, the mean RTs of errorless sequences per Participant and Key position obtained in the Single Stimulus test condition – which was identical for all participants - were analyzed with a 2 (Luminance condition during practice: Iso vs. Mix) × 4 (Key) mixed ANOVA with Luminance as a between-subjects variable. This ANOVA showed a significant main effect for Key position, $F(1.69, 37.27) = 83.10$, $p < .001$, $\eta_p^2 = .79$, indicating that RT decreased along sequential key positions. Moreover, prior practice with the mixed luminance condition (MixInc) led to shorter RTs in the Single Stimulus condition than practice with only isoluminant stimuli (IsoInc), $F(1, 22) = 5.97$, $p = .023$, $\eta_p^2 = .21$ (see Figure 11). There was no Key × Luminance interaction.

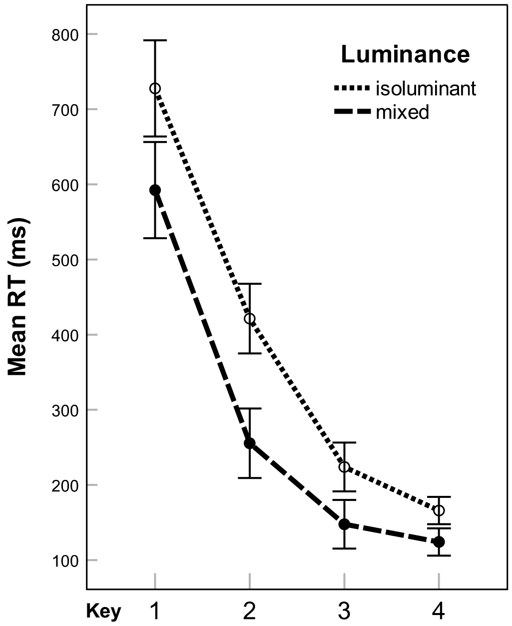

Figure 11: The effect of luminance during practice on mean RTs in the Single Stimulus condition of Experiment 2. Error bars indicate the SEM.

Next, mean RTs of errorless sequences per Participant and Key position obtained in the Random Sequence and Random Distractor conditions were analyzed with a 2 (Luminance condition during practice: Iso vs. Mix) × 2 (Condition: Random Sequence vs. Random Distractor) × 4 (Key) mixed ANOVA. It showed that like in Experiment 1 RTs were significantly slower in the Random Distractor condition than in the Random Sequence condition (485 ms vs. 420 ms), $F(1, 22) = 46.27$, $p < .001$, $\eta_p^2 = .68$. Again, there was a significant main effect for Key position, $F(1.79, 39.47) = 30.84$, $p < .001$, $\eta_p^2 = .58$, indicating that RTs varied across key positions. Furthermore, the Condition × Key interaction was marginally significant, $F(1.85, 40.78) = 2.74$, $p = .080$, $\eta_p^2 = .11$. The difference of luminance conditions during practice did not reach significance.

Arcsine transformed error proportions per Participant, Test condition and Key position obtained in the test phase were analyzed with a 2 (luminance condition during practice: Iso vs. Mixed) × 3 (Test Condition: Random, Random Distractor, Single Stimulus) × 4 (Key) mixed ANOVA. Again, luminance condition served as a between-subjects variable. The ANOVA showed main effects of Test Condition,

$F(1.17, 25.62) = 16.98$, $p < .001$, $\eta_p^2 = .44$, and Key, $F(3, 66) = 6.52$, $p = .001$, $\eta_p^2 = .23$, implying that more errors were made in the Single Stimulus condition than in the Random and Random Distractor condition (10.2 % vs. 3.6 % and 2.7 % per key, resp.) and that error rate varied across key positions (2.5 %, 7.5 %, 6.8 %, 5.2 %, resp.). There was no significant difference in error rates between the two Luminance conditions. The interaction between Condition × Key, $F(3.25, 71.43) = 15.74$, $p < .001$, $\eta_p^2 = .42$, showed that the error rates per key differed most in the Single Stimulus condition (2.5 % for R_4 vs. 17.3 % for R_2) and only little in the other two test conditions (1.2 % - 7.3 % per key).

7. Discussion

In Experiment 2 we tested whether displaying the first stimulus of each sequence with a different luminance than the background, and only the following stimuli in an isoluminant color, would result in faster RTs in the subsequent Single Stimulus condition and therefore boost sequencing skill. At the same time, by analyzing learning differences between the MixInc and IsoInc groups, we indirectly tested whether MixInc participants would eventually be able to ignore S_{234}, if only those were isoluminant and differed from the color of S_1. We expected that under those practice conditions, after a while participants would not be obliged anymore to process any of the isoluminant stimuli, because the first stimulus with a different luminance indicated which of the two sequences they had to produce. Consequently, after practice they would not need to use the processing mode in which attention is captured by isoluminant stimuli and develop stronger sequence representations.

The analysis of the practice phase showed that none of the two groups improved more than the other, which could mean that like the IsoInc group, also the MixInc group learned to deal with the incompatible S-R mappings and did not learn to ignore key-specific stimuli as we expected but did use their sequence representations. However, this can also be explained by the fact that initially, even the isoluminant S_{234} had to be processed in order to learn the sequences. Therefore, even though performance did not differ during practice, MixInc participants might have still learned to ignore S_{234} when they no longer needed those stimuli to execute the sequences. This presumption is supported by the results of the test phase: The analysis of the Single Stimulus test condition revealed that MixInc participants were faster in reproducing the practiced sequences than IsoInc participants. This indicates that MixInc participants indeed had learned to ignore the isoluminant S_{234} after they developed sequence representations. So, although performance during practice did not differ, MixInc participants were more used to not using R_{234} during practice than the IsoInc participants. Consequently, this finding confirms our hypothesis that using isoluminant later stimuli during practice supports the development of sequence representations and, hence, sequencing skill. It also confirms the finding that participants can prepare for processing stimuli of either different or the same luminance (Lambert et al., 2003), and our suspicion that they do not change this processing mode once they have started executing a familiar sequence.

Regarding S-R learning and the skill to suppress stimuli with a different luminance, we did not predict any differences between IsoInc and MixInc participants, since both groups practiced with the same incompatible S-R mappings and were used to isoluminant stimuli. This was confirmed by the results of Experiment 2. Finally, also in the Random Distractor condition of Experiment 2 neither of the two groups was better able to suppress an attention attracting stimulus. Again, this is what we expected, as none of the two groups was used to ignoring stimuli with a different luminance. This further supports our interpretation of Experiment 1 that isoluminant practice yields a tendency to take more time to identify a stimulus, irrespective of the actual luminance of the stimulus (Wong et al., 2017).

8. General Discussion

The purpose of the present study was to test whether participants develop stronger sequence representations in a DSP task if keying sequences are practiced when participants are persuaded to ignore guidance by the key-specific stimuli. To explore this hypothesis, we first compared four different practice conditions in Experiment 1, which distinguished two S-R mappings (*Com*patible vs. *Inc*ompatible) and the luminance of the stimuli (*Iso*luminant vs. *Dif*ferent luminance) and their combinations. Based on the results of Experiment 1, we developed a fifth practice condition (*Mix*ed luminance and *Inc*ompatible S-R mapping) and tested it in Experiment 2 in comparison to the IsoInc group. We further examined whether S-R learning would benefit from practice with compatible S-R mappings and whether the ability to suppress attention attraction towards a stimulus is a skill that participants can eventually learn under certain conditions.

Experiment 1 did not provide support for our initial hypothesis but revealed other interesting results. We hypothesized that the combination of isoluminant stimuli and incompatible S-R locations in the IsoInc group would persuade participants to ignore the key-specific stimuli that follow the first stimulus as soon as possible and that this would boost the development of sequencing skill. However, we found that the key-specific stimuli were still used after extended practice, which suggested that IsoInc participants did not learn to ignore key-specific stimuli as we expected but they still seemed to use their sequence representations. Moreover, the findings from Experiment 1 suggested that the Iso participants prepared a slower processing mode in which attention is captured by isoluminant stimuli to identify S_1 (Lambert et al., 2003). Once having identified S_1, the cognitive load of executing a sequence seems to have prevented them from changing to the mode in which attention is not captured by isoluminant stimuli. As a consequence, participants did not ignore the following key-stimuli and sequence learning did not improve. The development of the Experiment 1 was based to a large extent on the implications of Verwey (2020) and Verwey et al. (2020). Our findings support and further imply that even if participants can control whether they use isoluminant key-specific stimuli, they usually continue to use them when they are displayed, either because the following key-stimuli are still beneficial, as shown by Verwey (2020) and our compatible S-R condition (IsoCom and DifCom), or because they use a processing mode in which attention is captured by isoluminant stimuli (IsoInc and IsoCom).

Therefore, based on the results of Experiment 1, we developed a second experiment to test whether a color change between S_1 and S_{234} from a different luminance to an isoluminant color would enable participants to suppress stimuli with this particular feature value of isoluminance. We expected that practice under this mixed luminance condition would yield increased independence of S_{234} and, therefore, boost the development of sequencing skill. This was confirmed in Experiment 2, as the new MixInc group indeed showed greater independence of the following key-stimuli and faster RT in the Single Stimulus condition compared to the IsoInc group from Experiment 1. These results corroborate that ignoring key-specific stimuli strengthens sequence learning and that participants do not change the stimulus processing mode in which isoluminant stimuli attract attention.

Moreover, we initially predicted that compatible S-R mappings during practice (DifCom and IsoCom) would yield improved S-R learning in a Random Sequence condition as compared to the DifInc and IsoInc groups. This prediction was not confirmed. Instead, we found in Experiment 1 that practice with isoluminant stimuli resulted in slower RTs in reproducing random unfamiliar sequences. However, this luminance effect did not appear in Experiment 2. This suggests that in Experiment 1, the difference between Iso and Dif participants had not been caused by a familiarity advantage of Dif participants because MixInc participants (unlike IsoInc) were also used to reacting to the yellow attention attracting stimuli and still did not perform better than IsoInc. Instead, it corroborates our explanation that MixInc participants, like IsoInc participants had developed a strategy of taking more time for identifying stimuli (Wong et al., 2017), which persisted in the Random conditions and resulted in no difference between IsoInc and MixInc.

Next to that, we also tested whether the ability to suppress attention attracting stimuli is a skill that participants can eventually learn under certain conditions. We assumed that during practice with different luminant stimuli in incompatible S-R mappings (in DifInc), participants would have to actively suppress their attention to the location and would, therefore, learn to suppress the automated tendency to respond to that stimuli. However, S-R compatibility during practice did not have any effect on RTs in the random conditions. None of the groups was better able to suppress the distractor stimuli and we found no learning effects.

Relating our findings to the C-SMB model (see Figure 1), we can infer that during practice the feature of isoluminance of the key-specific stimuli might increase the processing demands on the perceptual processors. As those transmit their output to the central processor by loading a perceptual representation into short-term memory, even after extended practice when sequence representations have developed, this slower processing can still slow down sequence execution by the central processor. This is derived from our assumption that participants do not change the processing mode in which attention is attracted by isoluminant stimuli once they have started executing a familiar sequence. However, by changing the color of the first stimulus, we found a way to allow participants to ignore guidance by the key-specific stimuli so that after practice only the salient S_1 would capture attention and participants would not use a slower processing mode to process the isoluminant S_{234}.

Following the findings of our study, further research is needed to confirm that participants in Experiment 2 indeed learned to ignore the following isoluminant key-stimuli, as we only tested this indirectly by comparing learning differences between the IsoInc and MixInc group. Our experiment with the IsoInc and MixInc group should therefore be replicated (with a larger sample size) and possibly also include longer sequences of 6 or 7 keys, as those are typically used in the DSP task. Moreover, additional measures such as eye-tracking could be used to directly check whether participants start to ignore isoluminant key-specific stimuli. Finally, the error rates in the Single Stimulus condition of both experiments imply that participants might require more practice trials to fully develop sufficient sequence knowledge, especially when practicing with incompatible S-R mappings.

8.1. **Conclusions**

The results of the present study (a) show that ignoring key-specific stimuli strengthens sequence learning and (b) further suggest that participants prepared for identifying isoluminant stimuli, which reduced sequence learning relative to Experiment 2. The first experiment showed that in a familiar discrete keying sequence S_{234} continue to be used when they are isoluminant if S_1 forces them to use a slower processing mode in which attention is captured by isoluminant stimuli. Experiment 2 suggests that to allow participants to ignore guidance by the key-specific stimuli, the color of the first stimulus should differ from the following stimuli so that after practice, only the salient S_1 would capture attention and participants would not use a slower processing mode to process the isoluminant S_{234}.

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