

Learning a keying sequence you never executed: Evidence for independent associative and motor chunk learning[☆]



Willem B. Verwey^{a,b,c,*}, David L. Wright^c

^a Department of Cognitive Psychology and Ergonomics, Faculty of Behavioral Sciences, Universiteit Twente, PO Box 217, 7500 AE Enschede, The Netherlands

^b MIRA research institute, Universiteit Twente, PO Box 217, 7500 AE Enschede, The Netherlands

^c Human Performance Laboratories, Department of Health and Kinesiology, Texas A&M University, College Station, TX, USA

ARTICLE INFO

Article history:

Received 21 March 2014

Received in revised form 6 May 2014

Accepted 26 May 2014

Available online xxx

PsycINFO classification:

2330 motor processes

2340 cognitive processes

Keywords:

Keying sequences

Discrete sequence production task

Serial RT task

Processing modes

Associative sequence learning

ABSTRACT

A substantial amount of research has addressed how people learn and control movement sequences. Recent results suggested that practice with discrete key pressing sequences results in two types of sequence learning: associative learning and motor chunk development (Verwey & Abrahamse, 2012). In the present study, we addressed whether in keying sequences of limited length associative learning develops also when the use of the chunking mode is prevented by introducing during practice random deviants. In line with the notion of two different learning mechanisms, the present results indicate that associative sequence learning develops when motor chunks cannot be developed during practice. This confirms the notion that motor chunks do not rely on these associations. In addition, experience with a particular execution mode during the practice phase seems to benefit subsequent use of that mode with unfamiliar and random sequences. Also, participants with substantial video-gaming experience were faster in executing discrete keying sequences in the chunking mode. These last two results may point to the development of a general ability to produce movement sequences in the chunking mode.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

While in many tasks guidance of sequential motor skills is internal in that movement-specific stimuli are not required (e.g., Goldberg, 1985; Hikosaka et al., 1999), in some other tasks movement sequences are still controlled externally in that individual responses are guided by movement-specific stimuli (e.g., Cohen & Poldrack, 2008). Support for this distinction between internal and external control has been found also in serial key pressing tasks (Verwey & Abrahamse, 2012). Initially, these keying sequences are carried out by reacting to movement-key specific stimuli in the so-called reaction mode. In the case of a fixed keying sequence of limited length (e.g., in the discrete sequence production, or DSP task, Verwey, 2001) practice is assumed to yield integrated memory representations for that sequence that have been called motor chunks. According to the Dual Processor Model these motor chunks are selected as a unit by a cognitive processor, and then executed by

an independent motor processor (Verwey, 2001; for reviews, see Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013; Rhodes, Bullock, Verwey, Averbek, & Page, 2004). Keying sequences executed in this way are said to be executed in the chunking mode. The chunking mode is characterized by the fact that participants make little or no use of the movement-specific stimuli—except for the first one to determine the proper motor chunks.

Indications for a second sequence learning mechanism come from studies using the serial reaction time (serial RT) task (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Nissen & Bullemer, 1987). This task also involves reacting to movement-specific stimuli in the reaction mode. Here participants cycle repeatedly and without interruption through a single sequence consisting of, typically, 12 successive key presses. Despite practice, participants continue to respond to each movement-specific stimulus, and they often do not even notice that there is a sequence at all. Still, responses in the practiced sequence get faster than in a random sequence which is solely based on continued selection of each key. The responsible learning mechanism is assumed to involve the development of associations between representations involved in sequentially reacting to movement-specific stimuli. When these associations develop, the reaction mode gradually changes into the associative mode (Verwey & Abrahamse, 2012). These associations develop at perceptual, central, and motor levels of processing, and they allow priming of the representations used for the ensuing

[☆] We would like to thank Diana Becker, Luisa Breddemann, Gina Ehling, Corinna Gerst, Lotte van der Lelij, Isabel Moning, and Sebastian Schiller for running the experiment.

* Corresponding author at: University of Twente, Department of Cognitive Psychology and Ergonomics, Faculty of Behavioral Sciences, PO Box 217, 7500 AE Enschede, The Netherlands. Tel.: +31 53 489 3611/4764; fax: +31 53 489 4241.

E-mail addresses: w.b.verwey@utwente.nl (W.B. Verwey), d-wright@hlkn.tamu.edu (D.L. Wright).

responses (for a review, see Abrahamse, Jiménez, Verwey, & Clegg, 2010). This associative mechanism allows sequence learning even in probabilistic sequences in which some of the stimuli deviate from a fixed order so that no element can be predicted with certainty (e.g., Jiménez & Méndez, 1999; Schvaneveldt & Gomez, 1998). Apparently, associative learning of a base sequence is not prevented by occasional deviations. It has been argued that associative sequence learning is based on associations between pairs and probably also triplets of stimuli and movement representations (i.e., statistical learning, Perruchet & Pacton, 2006), rather than that a particular movement sequence is being learned.

While skilled execution of DSP sequences has always been assumed to rely on the use of motor chunks, Verwey and Abrahamse (2012) proposed that practice in this task induces associations between successively used representations, too, just like in the serial RT task. This idea was initially based on findings that many older participants improved their execution of discrete keying sequences while they did not exhibit indications for using motor chunks (Verwey, 2010; Verwey, Abrahamse, Ruitenberg, Jiménez, & De Kleine, 2011). Also, when color coding in a serial RT task seemed to induce the use of motor chunks, subsequent removal of color coding made the indications for motor chunk use disappear, but effects of practice remained (Jiménez, Méndez, Pasquali, Abrahamse, & Verwey, 2011). To examine whether sequence learning in the DSP task also yields associative learning in younger people – in parallel to motor chunk development – Verwey and Abrahamse (2012) had young adults practice two 6-key sequences in the normal DSP task way. In the ensuing test phase, these participants were kept from using motor chunks by introducing in 75% of the sequences, stimuli at two random positions that deviated from the learned order. As a result they were forced to react to all movement-specific stimuli again. As expected the execution rate of the occasional sequences in this condition that did not include these deviants was lower than when these sequences were produced in a condition without such deviants. More importantly, execution rate was still higher than that of comparable sequences that were unfamiliar. Verwey and Abrahamse (2012) argued that the possibility that deviants would occur kept participants from using motor chunks. Still, these participants did benefit from the associations that had developed in parallel with the motor chunks. This account was supported by the observation that the RT distributions in these familiar sequences were shifted as a whole relative to those obtained with the pure-familiar and unfamiliar sequences, but they had not widened. So, the faster execution rate could not be explained by participants alternating the chunking and reaction modes.

One may wonder whether the associations assumed to underlie associative sequence learning are independent of the chunking mechanism. It is possible that the same associations underlie associative sequence learning and motor chunk development, and that the difference is merely whether or not successively selected movements are first temporarily buffered in the chunking mode, or are immediately executed one after the other in the associative mode. If so, associative sequence learning may not develop if during practice the use of motor chunks is prevented and participants continue to perform the sequences in the reaction mode. In contrast, the notion that associative sequence learning involves independent mechanisms at the perceptual, central, and motor levels of information processing (Abrahamse et al., 2010; Goschke & Bolte, 2012) predicts that associative sequence learning can develop even when motor chunks do not.

To explore whether associative sequence learning and motor chunk development involve independent sequence learning mechanisms, we designed a study in which participants in the deviant practice group practiced two 6-key DSP sequences that always contained one deviating stimulus. This deviating stimulus was determined randomly for each trial, and could occur at any location except the first. It forced participants to continue reacting to individual stimuli while practicing the sequences. They were not able to use motor chunks because they never executed the underlying base sequence without deviant during

practice. Nevertheless, the findings of sequence learning in probabilistic versions of the serial RT task (Abrahamse et al., 2010) suggested that in this condition sequential associations could still develop. With this setup we tested whether associative sequence learning develops in case motor chunks cannot be used, and whether the development of associative sequence learning may perhaps still allow the later use of motor chunks. To assess performance in a condition in which motor chunks do develop, the non-deviant practice group practiced the same two sequences without deviants, that is, the base sequences themselves.

The notion that associations develop in the deviant practice group predicts that when deviants do not occur anymore in a subsequent test condition, the deviant practice group should be faster on the base sequence (that they actually never encountered during practice) than on an entirely unfamiliar sequence. Yet, they should still be slower than the non-deviant practice group because they did not develop the required motor chunks, while the non-deviant practice participants did.

A further research issue concerned whether prior experience with the associative mode (in the deviant practice group) or chunking mode (in the non-deviant practice group) influences the execution of unfamiliar sequences. To examine this, we also introduced a random test condition. In this random condition, each stimulus was randomly selected during runtime (though preventing repetitions) so that there was no fixed order at all. This condition allowed us to assess response times in case there is no fixed order, that is, in a pure reaction mode. This condition served as baseline to see whether participants improve on the unfamiliar, fixed sequences in the course of a single test block. If prior experience with a particular mode helps using that mode with unfamiliar sequences, one can expect the deviant practice group (that extensively used the reaction mode during practice) to be faster on random sequences in the test phase than the non-deviant practice group (that had been using the chunking mode during practice). Conversely, non-deviant practice group participants may be faster in unfamiliar but fixed sequences that allow a quick use of the chunking mode. The potential finding of a group by sequencing mode interaction would support the notion that people can develop a general skill in using the associative or the chunking mode—even in a sequence that is unfamiliar.

In short, the present study addressed if a) associative learning develops even when motor chunks are not used during practice, b) such associations may still allow the subsequent use of the chunking mode, and c) experience with a particular execution mode may facilitate later use of the mode.

2. Method

2.1. Participants

Forty-eight undergraduate students took part in exchange for course credits (average age: 20.9, age range: 17–25 years, 24 women). The study was approved by the ethics committee of the Faculty of Behavioral Sciences of the University of Twente.

2.2. Apparatus

Stimulus presentation, timing, and data collection were achieved using the E-prime© 2.0 experimental software package on a standard Pentium© IV Windows XP© PC. Unnecessary Windows services were shut down to improve RT measurement accuracy. Stimuli were presented on a 17 inch Philips 107T5 display running at 640 by 480 pixel resolution in 16 bit color, and refreshing at 85 Hz. The viewing distance was approximately 50 cm, but this was not strictly controlled.

2.3. Task, sequences and stimuli

Six black 9 × 9 mm placeholders were displayed on a computer display with a white background. Between each placeholder there was a

7 mm distance, except between the third and the fourth placeholder where a 22 mm gap was presented to mimic placement of the (DFG and JKL) keys at the keyboard on both sides of the H key. As soon as a placeholder was filled with green, participants pressed the spatially corresponding key with their left or right ring, middle, or index finger. When the correct key had been pressed, the color in the placeholder changed back to the white background color for 50 ms after which the next stimulus was presented (i.e. response stimulus interval was 50 ms), and so on, until a full sequence was executed.

Each participant responded to two series of six stimuli (i.e., S_1 – S_6). This yielded the two 6-key sequences (R_1 – R_6). Notably, the 50 ms response-to-stimulus interval (RSI) differs from the typical DSP task with its typical 0 RSI. This non-zero RSI allowed participants to perceive an occasional repetition of the same key which could occur in case of a random deviant. This setup implies that in the practice and test phases the inter-key interval equaled the time between the moment of stimulus presentation and the moment of responding (i.e., response time, or RT), plus 50 ms. RTs between S_n and R_n are denoted T_n (e.g., RT between S_2 and R_2 is T_2). The term ‘trial’ is used in the present study to denote a 6-key sequence.

Following a sequence the display was erased with the white background color for 1000 ms to indicate sequence completion. Then the six placeholders were presented again for 1000 ms and the first stimulus of the next sequence was displayed. Pressing an incorrect key resulted in an error message for 2000 ms, after which the ongoing sequence was aborted, and a 1000 ms empty screen followed. The next sequence then started with its 1000 ms presentation of the six placeholders.

Each practice block included 180 trials, 90 of each sequence. With 6 practice blocks this yielded a total of 540 practice trials for each sequence. Halfway through each practice block there was a 40 s resting period and each practice block was followed by a rest period of 4 min. Each practice block part was ended by feedback on the percentage of errors and mean RT.

Across all participants keys in the base sequences were rotated across sequential positions so that each of the six fingers contributed as much to the RT at each sequential position. This yielded 6 different sequences. Each participant practiced two of these 6 sequences as familiar sequences and, in the test phase, two others as unfamiliar sequences. For example, one participant executed KFGDJL and FKLJDG, while the next participant had LGJFKD and GLDKFJ, and so on. The order of the two 6-key sequences was random.

Half of the 48 participants performed in the non-deviant practice group, and the other 24 in the deviant practice group. Participants were randomly assigned to one of the two groups. The non-deviant practice group practiced two 6-key unaltered (‘base’) sequences. The deviant practice group performed the same sequences, but during the practice blocks one of the key presses at sequential positions 2 to 6 was always changed. This key was randomly chosen, and was never equal to the original key at that position, or one of the preceding two keys. It did happen that the randomly selected key was equal to the ensuing key, so that the key was repeated. To prevent participants from thinking that their key press had not been detected when a stimulus was displayed twice, there always was a 50 ms pause between each key press and display of the next stimulus. Participants had been warned in advance of practice that sometimes a key press might be repeated (which actually was not the case with the non-deviant practice group). Participants of both groups were not informed about the order of the key presses and whether or not there was a random deviant.

The test phase was identical for the two practice groups. It included three blocks of 50 trials, each including another experimental condition. These blocks were separated by a 40 s pause and the order of these three blocks was counterbalanced across the participants. One test block contained the familiar sequence condition. Sequences in this test condition did not include a deviant so that for the non-deviant practice group these sequences were identical to the ones they had been practicing before. These participants were assumed to execute these sequences

in the chunking mode. However, while being used as base sequence for the deviant practice group, this sequence had not yet been encountered as a whole by the deviating practice group participants. The second test block involved the unfamiliar sequence condition. This condition involved two sequences from the set of six alternative sequences that had not yet been performed by any participant. Across participants the same set of 6 sequences occurred equally often in the familiar and unfamiliar conditions. The third test block included the random condition. It consisted of a 6-key sequence of which each next key was selected randomly during each trial (except that a key was never repeated). These sequences were necessarily carried out in the reaction mode.

2.4. Procedure

Upon entering the lab, the participants filled out an informed consent form and received a written instruction on the task to be performed. If necessary this was extended orally by the experimenter. Then the 6 practice blocks were carried out. They were asked to respond quickly but to keep errors below 8%. Participants were warned during feedback display if they exceeded this error threshold. An error led to the sequence being broken off, and the display of an error message.

After the practice phase, participants filled in a questionnaire. The first part asked the participants to write down their sequences from memory (after they were told they had been executing two 6-key sequences). Next, the questionnaire asked them to recognize their two sequences from 18 alternatives. The participants were then asked whether they had remembered their sequences by a) recalling the order of the letters on the keys, b) tapping the sequences with their fingers on the table top or in their mind, c) remembering the positions of the successive stimuli and/or keys, and d) some other strategy. These questions are standard in recent DSP studies. Next, participants were asked about their experience with various perceptuomotor skills. This section included four questions asking for experience with playing videogames, playing the piano, playing any other musical instruments (also asking to indicate which instrument), and performing a particular sport (also asking which sport). The participants' experience with these activities was assessed by asking for each, a) whether they practiced less than 1 h per week, 1–7 h per week, and 1–7 h per day (scores 1–3), b) whether they had done that for less than 1 year, 1–5 years, or more than 5 years (scores 1–3), and c) whether they had done so until less than 1 month ago, less than 3 years ago, or more than 3 years ago (scores 3–1). Finally, the participants executed the test phase with its three blocks. The duration of the experiment was about two and a half hours.

3. Results

3.1. Practice phase

Response times (RTs) of correct sequences in the practice phase (blocks 1–6) are depicted in Fig. 1. It confirms the expectation that the presence of a single deviant at an unpredictable position kept participants of the deviant practice group from learning to rapidly execute their keying sequences. These RTs were analyzed with a mixed 2 (practice group: deviant vs. non-deviant) \times 6 (block) \times 6 (key) ANOVA on mean RTs per participant and block. Main effects of practice group, $F(1,46) = 80.4, p < .001$, block, $F(5,230) = 268.7, p < .001$, and key, $F(5,230) = 92.5, p < .001$ were significant. All interactions were significant too, practice group \times block, $F(5,230) = 41.1, p < .001$, practice group \times key, $F(5,230) = 96.0, p < .001$, block \times key, $F(25,1150) = 7.9, p < .001$, and practice group \times block \times key, $F(25,1150) = 16.1, p < .001$. Separate planned comparison for each group confirmed that not just the non-deviant but also the deviant practice group showed improvement across the practice phase, $F_s(5,230) > 50.0, p_s < .001$.

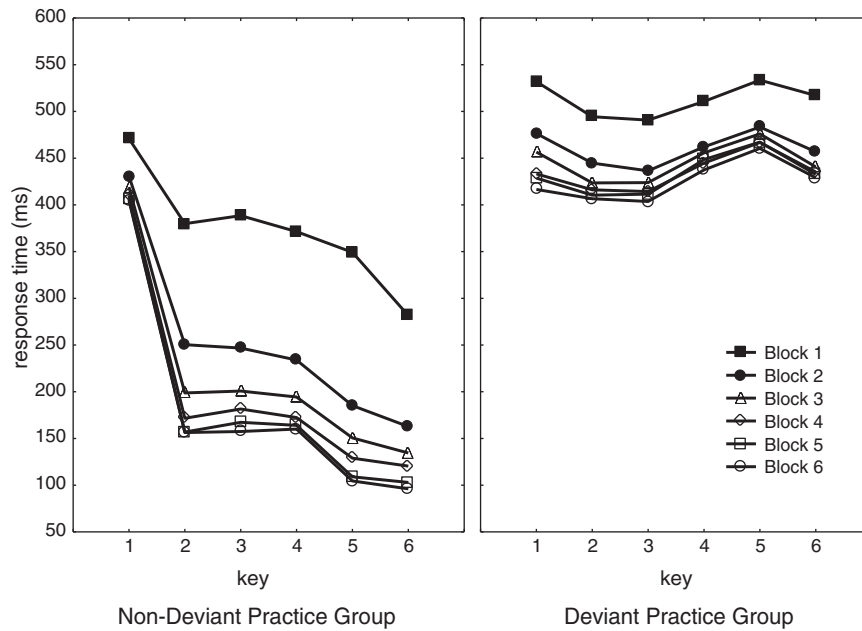


Fig. 1. Response times in the two practice groups as a function of block and key.

Fig. 2 shows for the deviant practice group the RTs separately for deviant and non-deviant stimuli. The RTs of the deviant practice group were analyzed in a within-subject 2 (deviant: deviant vs. non-deviant stimulus) × 6 (block) × 5 (key 2–6) ANOVA on mean RTs per participant, block and key (key 1 never involved a deviant). In this ANOVA, all main effects and interactions were significant. The main effects were deviant: $F(1,23) = 82.6, p < .001$; block: $F(5,115) = 59.4, p < .001$; key: $F(4,92) = 20.9, p < .001$, and the interactions deviant × block: $F(5,115) = 46.9, p < .001$; deviant × key: $F(4,92) = 10.4, p < .001$; block × key: $F(20,460) = 1.6, p < .05$; deviant × block × key: $F(20,460) = 2.5, p < .001$. Planned comparisons showed that RTs reduced with practice, not only for responses to non-deviants (from 503 ms in block 1 to 412 ms in block 6), $F(5,115) = 87.1, p < .001$, but also for responses to deviant stimuli (from 538 to 490 ms), $F(5,115) = 28.1, p < .001$. Fisher LSD-post hoc tests of RTs of all five

sequential responses in the deviant practice group showed that across all six practice blocks the relatively fast R₂–R₃ (right-hand frame of Fig. 1) were caused by these responses being especially fast when they did not deviate (left frame of Fig. 2). That is, R₂ and R₃ were faster than R₄, R₅, and R₆ (all $ps < .01$), but R₂ vs. R₃, and R₄ vs. R₆ were not different. In contrast, responses to the deviant stimuli were not different across R₂–R₆ ($ps > .06$, right frame of Fig. 2). Post hoc tests revealed also that the responses at each sequential position were given faster in response to non-deviant than to deviant stimuli (all $ps < .05$).

Error analyses involved ANOVAs on arcsine-transformed errors. Winer, Brown, and Michels (1991) recommend this transformation when data with binomial distributions, such as error proportions, are analyzed with parametric tests. A mixed 2 (practice group) × 6 (block) ANOVA on arcsine transformed proportions of sequences with an error showed that there were more erroneous sequences in the

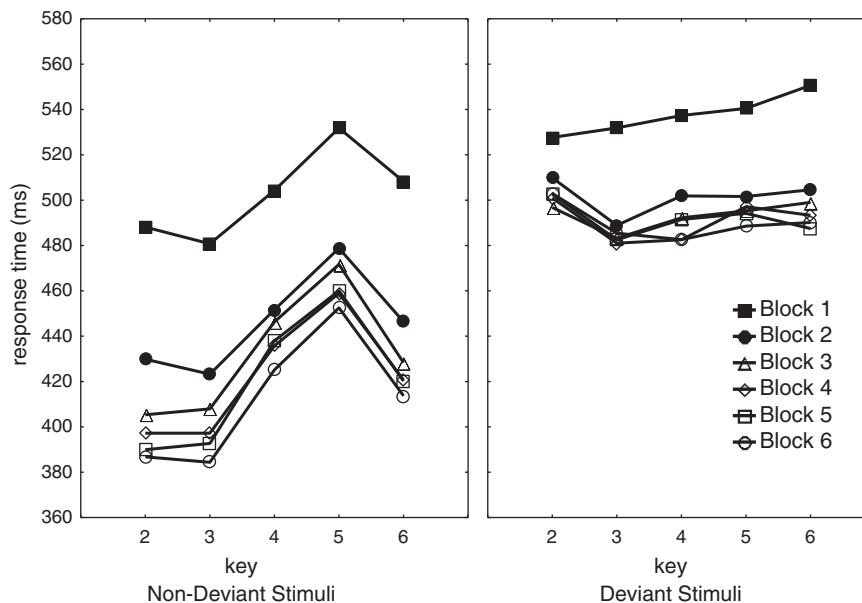


Fig. 2. Response times in the deviant practice group to non-deviant stimuli and to deviant stimuli as a function of block and key.

deviant than in the non-deviant practice group, 9.0% vs. 4.6% respectively, $F(1,46) = 13.5, p < .001$, and that error proportion increased with block, from 5.5% in block 1 to 8.1% in block 6, $F(5,230) = 9.9, p < .001$. We then used a mixed 2 (practice group) \times 6 (block) \times 6 (key) ANOVA which confirmed that error rate per key press increased with block, $F(5,230) = 7.7, p < .001$. Also, a key main effect, $F(5,230) = 16.8, p < .001$, and a practice group \times key interaction, $F(5,230) = 11.2, p < .01$, showed that error rate was relatively low at the first and last sequence positions of the non-deviant practice group, 0.8% and 0.6% (remaining keys: 1.2–1.8%), whereas in the deviant practice group error rate was 0.8% at R_1 and 3% at R_2 , after which it gradually rose from 2.4% at R_3 to 2.9% at R_6 . In the deviant practice group, R_2 and R_6 especially suffered from high error rates when a deviating stimulus appeared in that R_2 and R_6 had error rates of 3.4% and 3.5% in block 6, as if these responses were the hardest to change in case of a deviant.

3.2. Test phase

The RTs obtained in the test phase – that was identical for both groups – were analyzed with a mixed 2 (practice group: deviant vs. non-deviant) \times 3 (sequence: familiar, unfamiliar, random) \times 6 (key) ANOVA on mean RTs per participant, condition, and key position. Sequences with execution times that exceeded the average RT plus 3 SD in each condition were removed. This eliminated the contribution of 1.1% of the sequences. Main effects of practice group, $F(1,46) = 7.2, p = .01$, sequence, $F(2,92) = 140.7, p < .01$, and key, $F(5,230) = 84.8, p < .01$ were found. All interactions were significant, $ps < .001$. The practice group \times sequence interaction, $F(2,92) = 31.3, p < .001$, confirmed that the deviant practice group was substantially slower than the non-deviant practice group in the familiar sequence (Fig. 3). Planned comparison showed that the non-deviant and the deviant practice group were both faster on the familiar than on the unfamiliar sequence, $F_s(1,46) > 4.78, ps < .04$. For the deviant practice group, the latter effect supports the main hypothesis that practice with deviants supports execution of the base sequence even though these participants had never executed that sequence before.

To explore whether experience with a particular mode would benefit later use of that mode with other sequences, we examined if the deviant practice group would be the fastest in the random condition (due to their experience with the reaction mode), and the non-deviant practice group would be the fastest on the unfamiliar sequence (due to their experience to stop reacting to individual stimuli and engage in the chunking mode). Fig. 3 shows that the mean RTs are

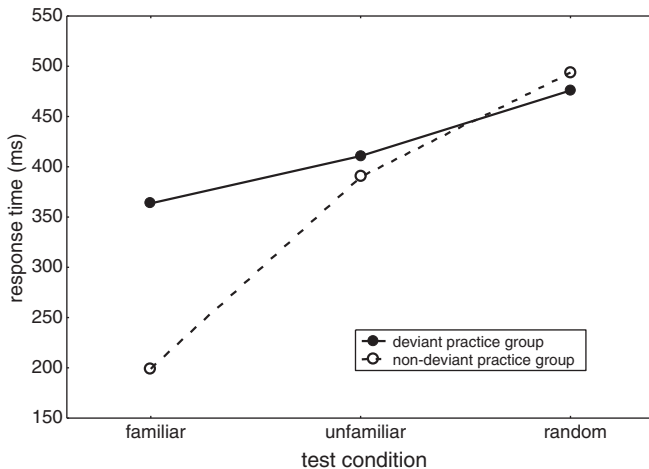


Fig. 3. Mean response time across all six key presses in each of the three test conditions for participants in the groups that had practiced with and without deviants.

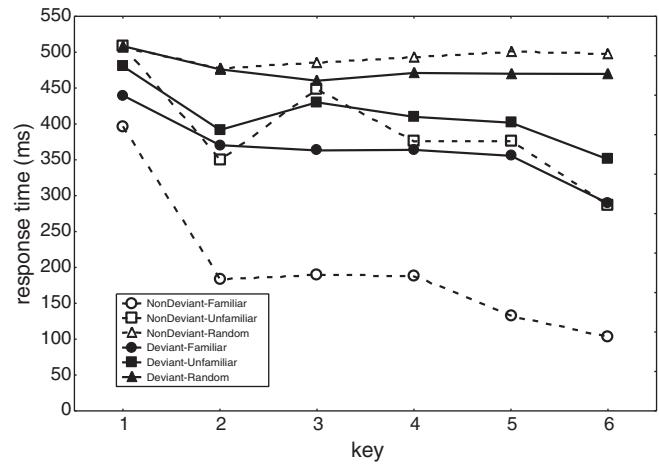


Fig. 4. Mean response time as a function of sequential position and test condition for the participant groups that practiced with and without deviations.

in line with this idea. Statistical support was provided by a mixed 2 (practice group) \times 2 (sequence: unfamiliar, random) \times 5 (keys 2–6) ANOVA on mean RTs per participant, condition and key position. This ANOVA showed a practice group \times sequence interaction, $F(1,46) = 3.9, p = .05$ (Greenhouse–Geisser correction not needed), confirming a 30 ms advantage across keys 2–6 for the non-deviant practice group in the unfamiliar sequence, and a 22 ms advantage of the deviant practice group in the random sequence. Fig. 4 indicates that the advantage of the unfamiliar sequence over the random sequence in both practice groups lays in R_2, R_4, R_5 and especially R_6 .

A mixed ANOVA with a 2 (practice group) \times 3 (sequence) ANOVA on arcsine transformed proportions of sequences with an error was highest in the random condition (10.4%), less in the unfamiliar sequences (8.2%), and least in the familiar sequences (6.7%), $F(2,92) = p < .001$. A group difference was not observed, $F(1,46) = 2.0, p = .16$. A subsequent ANOVA with a 2 (practice group) \times 3 (sequence) \times 6 (key) design on arcsine transformed error proportions confirmed that error rate per key was lowest in the familiar sequence, $F(2,92) = 19.1, p < .01$. Furthermore, a sequence \times key interaction, $F(10,460) = 4.0, p < .001$, showed that error rate in the familiar sequence peaked at R_3 – R_5 (about 2.4%), in the unfamiliar sequence at R_3 (3.4%), and in the random sequence at R_2 and R_6 (both 3.7%). In fact, the error pattern in the random sequence (low at R_3 – R_5) mirrored the one in the familiar sequence (high at R_3 – R_5).

3.3. Questionnaires

Table 1 presents the recall and recognition scores of the participants as assessed following the practice phase. It confirms that a substantial number of participants had no or limited awareness of the sequences that they had been executing during practice. The number of fully aware participants (i.e., those able to write down both their sequences) was considerably lower in the deviant than in the non-deviant practice group as indicated by an analysis of recall performance, $\chi^2(1) = 23.8, p < .001$, and of recognition performance, $\chi^2(1) = 12.3, p = .001$. Table 1 indicates also that those non-deviant practice participants who had correctly recalled and/or recognized both their sequences relatively often indicated to have reconstructed explicit knowledge of the sequences by ticking the sequence with their fingers, either on the table or mentally. Deviant practice group participants apparently were not able to tick the sequences like the non-deviant practice group participants. Still, within each practice group, higher recall or recognition performance was not significantly correlated with sequence initiation and/or average execution rate across all practice blocks ($rs < -.32, ps > .05$), and neither for individual practice and test blocks.

Table 1

The numbers (and percentages) of the participants of each practice group correctly recalling (by writing freely) or recognizing (by selecting 2 out of 18 given sequences) 0, 1, or 2 of their two 6-key sequences in the non-deviant and deviant practice groups. The lower four lines indicate for those participants who did recall/recognize both their sequences what strategies they had been using in the recall/recognition task.

Sequences correct	Non-deviant practice group (n = 24)		Deviant practice group (n = 24)	
	Recall	Recognition	Recall	Recognition
0	5 (21%)	1 (4%)	21 (88%)	7 (29%)
1	5 (21%)	0 (0%)	3 (12%)	11 (46%)
2	14 (58%)	23 (96%)	0 (0%)	6 (25%)

Subjective strategy of the participants who recalled/recognized both their sequences	Non-deviant practice group (n = 24)		Deviant practice group (n = 24)	
	Recall	Recognition	Recall	Recognition
Letter order	2 (14%)	4 (17%)	–	0 (0%)
(Mental/physical) ticking with fingers	9 (64%)	15 (65%)	–	1 (17%)
Stimulus/response locations	1 (7%)	2 (9%)	–	3 (50%)
Other	2 (14%)	2 (9%)	–	2 (33%)

Given that the second and third responses, and the responses at the end of discrete sequences are often quite fast, we were interested in whether this could be explained by a higher awareness of responses at the start and at the end than in the middle. This was tested by determining the numbers of correct keys in the recall questionnaire for each participant when counting from the sequence start and counting from the sequence end. For example, when in the case of sequence FKLJGD participants had written FKJLDG (and had reversed the middle two responses), counting from the start yielded 2 correct responses (namely FK), and counting from the end yielded 2 correct responses (namely DG). Next, the number of correct keys in the recall test at each sequential position was summed across each of the practice groups. The results of this analysis are depicted in Fig. 5. This figure confirms that across the

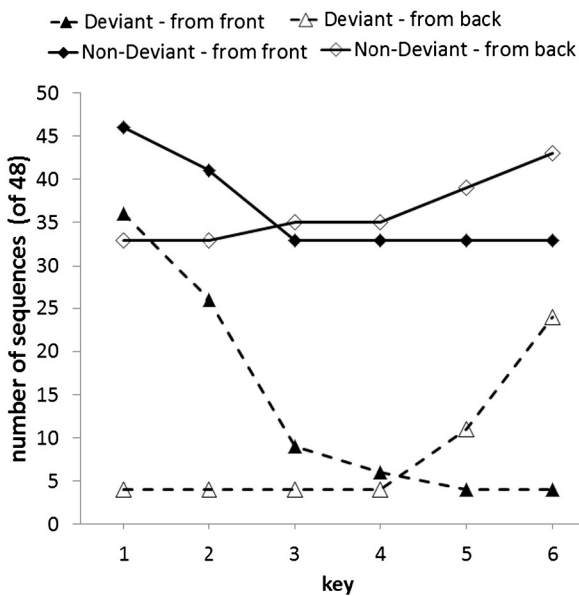


Fig. 5. The number of correct responses in the recall questionnaire across the 24 participants in the non-deviant practice group, and across the 24 participants of the deviant practice group (each with 2 sequences). The numbers at the Y-axis indicate the numbers of correct responses counted from the start of the sequence (R_1), and from the end (R_6). Notice that R_1 in the deviant practice group never included a deviant.

participants of each practice group, the first and (also!) the last few responses were recalled relatively well. Even in the deviant practice group, about half of the participants ended their written sequence with the correct last response.

Given the relatively high awareness of the first and last responses, we then examined whether correct recall of each response in a sequence correlated with the response time of that key press for individual participants in a practice group. These correlations were not significant. This strongly suggests that explicit knowledge does not contribute to execution rate. This is confirmed by a comparison of Figs. 1, 2 and 5. Fig. 5 shows that participants in both practice groups recalled R_3 more poorly than R_2 . Still, Figs. 1 and 2 show that the participants in both practice groups were about as fast on R_2 and R_3 . The only significant correlation between recall and execution rate was found in the first practice block of the deviant practice group where a better recall of R_6 correlated with a faster R_6 , $r = -.41$, $p < .05$. So, while across the participants in each practice group awareness and execution rate were higher for R_2 , R_3 , and R_6 , no significant correlations were observed indicating that individual participants with more awareness of these stimuli and responses also executed those responses faster.

The three scores for each individual real world perceptuomotor skill assessed in the questionnaire were summed into a compound experience score. On this scale of 3 (no experience) to 9 (extensive and recent experience) the average experience with video gaming was 5.3 in the non-deviant practice group, and 5.8 in the deviant practice group. For piano playing, other musical instruments and various sports these subjective experience scores amounted to 4.0 and 4.3, 3.3 and 3.5, and 6.4 and 6.8, respectively. Next, correlations were computed between experience with these real world tasks, and sequence initiation (indexing sequence selection) and sequence execution (indexing the use of the chunking and associative modes in the non-deviant and deviant practice groups, respectively). These correlations showed that in the non-deviant practice group individual experience in video gaming correlated with sequencing execution rate across all practice blocks ($r(n = 24) = .49$, $p < .015$). Experience scores on the other real world tasks (piano playing, other musical instruments, and sports in general) in this practice group, and experience with all four real world tasks in the deviant practice group, did not correlate with sequencing performance. More detailed analyses of video gaming experience with performance in the non-deviant practice group showed that video gaming experience was associated with a higher execution rate in each of the 6 non-deviant practice blocks (correlations ranging from $-.45$ to $-.55$, $ps < .05$). Furthermore, in this practice group, T_1 in early practice blocks 1 and 3 correlated significantly with video gaming experience too, $rs > -.41$, $ps < .05$ (blocks 2 and 4 to 6: correlations were $-.38$, $-.34$, $-.30$, $-.31$, respectively). Together, these findings suggest that experience in playing video games benefits the execution of motor chunks, and the initiation of the first response of a developing motor chunk. Video gaming skill does not seem to benefit responding in the reaction and associative modes (as used by the non-deviant practice group).

4. Discussion

As indicated in the Introduction, execution of keying sequences may become faster with practice not only by gradually responding more rapidly to individual stimuli (i.e., the associative mode), but also by executing key presses in short bursts that no longer require guidance by stimuli (i.e., the chunking mode). A previous study suggested that when practicing a typical DSP task associative learning occurs in parallel to the development of motor chunks (Verwey & Abrahamse, 2012). This may imply either that different, independent mechanisms can be used to support successful performance of a keying sequence, or that a single knowledge base is central to expressing sequence knowledge in different execution modes. The present results are in line with the existence of unique associative and motor chunk representations that can contribute to successful production of a practiced sequence. Introducing a

deviant during practice kept participants from developing motor chunks because they were forced to continue responding to individual stimuli. Still, this did not keep these participants from executing the ‘familiar’ base sequences relatively fast in the test phase despite the fact that they had never encountered these base sequences before. Apparently, participants in the deviant practice group could successfully perform the familiar base sequence because of associations that they had developed. Still, their performance was slower than that of the non-deviant practice group, confirming that they did not base their skill on motor chunks. The present results, then, support the suggestion that the development of associative sequence knowledge is independent of the development of motor chunks. This actually is not a surprising idea given that associative sequence learning is probably based on associations at all processing levels – perceptual, central, and motor (Abrahamse et al., 2010) – whereas motor chunks are likely to only involve associations at the motor level (Abrahamse et al., 2013).

We explored also whether experience with a particular – reaction or chunking – sequence execution mode influences the way in which an unfamiliar sequence is performed later on. Consistent with this possibility, the results showed a general advantage of the non-deviant practice group on the unfamiliar sequence in the test phase (suggesting the more rapid use of motor chunks), and an advantage of the deviant practice group on the random sequence in the test phase (suggesting a tendency to respond more rapidly to individual stimuli in the reaction mode). Further analyses showed that the benefit of the deviant over the non-deviant practice group in the random sequence occurred on R₃–R₆, that is, especially with later responses (Fig. 4). This gradual slowing of random, discrete sequences has been observed before (Fig. 3 in De Kleine & Verwey, 2009). The present data suggest that experience with the reaction mode – here in the deviant practice group – counteracts this performance reduction at the end of a random sequence. Hence, the present results confirm that experience with a particular execution mode benefits the execution of unfamiliar/random sequences in that particular mode.

Further analyses indicated that the advantage in executing the unfamiliar over the random sequence was, for both practice groups, in R₂, R₄, R₅ and especially R₆. The relatively fast R₂ and R₆ in an unfamiliar 6-key sequence have been observed in several earlier DSP experiments too (see the young participants in Fig. 2 in Verwey, 2010; Fig. 2 in Verwey, Abrahamse, & De Kleine, 2010; and Fig. 2 in Verwey, Abrahamse, & Jiménez, 2009). While the present recall data concern the familiar sequences, these awareness results do suggest that in unfamiliar sequences, too, R₂ and R₆ benefitted from rapidly developing explicit sequence knowledge of especially these two responses. However, the benefit of explicit knowledge may occur only in case responses are carried out quite slowly (like in relatively unfamiliar sequences) as the data did not show that awareness of the familiar sequences was correlated with execution rate of these rapidly executed responses. That is, in the present study participants who were fully aware of both sequences were not faster than those who were not fully aware (sometimes a slight execution rate benefit is observed, Verwey, 2010; Verwey et al., 2009, 2010). Furthermore, awareness of the second, third and sixth responses across all participants in each practice group (i.e., including the less aware participants) did not correlate with execution rate of the responses. Applying explicit knowledge may be too slow to contribute to the rapidly executed familiar sequences. In fact, it may well work the other way around: When asked, participants with perfect recall and/or recognition performance very often indicate that they base their recall/recognition performance on (rerunning) implicit knowledge, instead of explicit knowledge supporting sequence execution (present experiment; Verwey & Abrahamse, 2012; Verwey et al., 2009, 2010). That is, expressing sequence knowledge in another way than pressing keys may well involve reconstruction on basis of implicit knowledge rather than that explicit memories are used to increase execution rate. Consequently, it seems that not only executing highly practiced key sequences relies on implicit sequence knowledge, but recalling and

recognizing sequences does too (probably with the exception of the first and last responses that are recalled explicitly).

We evaluated also whether skill in a sequential real world task might benefit performance in a discrete sequential keying task. The reasoning was that people may develop general sequencing skills in these real world tasks that they can apply in other task environments too. For example, there are many reports now that video game players show more implicit serial RT task learning (Romano Bergstrom, Howard, & Howard, 2011), are better in surgical skills (Rosenthal et al., 2011), and actually have different saccadic trajectories (West, Al-Aidroos, & Pratt, 2013). We addressed this issue by assessing whether the amount of experience that our participants had with four serial real world tasks (namely playing video games, playing the piano, playing other musical instruments, and performing some sports) is correlated with performance on the sequences performed in the various execution modes. The correlational analyses show that skilled video gamers in the non-deviant practice group executed their DSP keying sequences faster, and were initially also faster initiating these sequences. This suggests that they develop and use motor chunks more quickly than participants with less or no video gaming experience (a similar tendency was found with regular pianists). This may be related to these participants more quickly releasing cognitive control – allowing the motor system to do its work – or to video gamers being able to make more rapid finger movements. This correlation was not observed for participants in the deviant practice group that relied on associative sequence learning, suggesting that video gamers are not faster in responding to stimuli and developing the associations assumed to underlie the associative mode.

Together the present results and the earlier Verwey and Abrahamse (2012) study indicate that in discrete keying sequences associative sequence learning develops independently of motor chunks. In the present experiment, this resulted in participants in the deviant practice group being faster on a base sequence that they had never carried out, than on an unfamiliar sequence. This is consistent with the idea that the associative mode is based on associations at various processing levels while motor chunks are based on a representation at the motor level of processing. The present results indicate also that experience with the reaction or the chunking mode may influence which mode is preferred when unfamiliar sequences are being learned. This tendency to use a familiar sequence execution mode may explain the present finding that participants with substantial video-gaming experience were faster in executing DSP sequences in the chunking mode than those with little experience in that real world task.

References

- Abrahamse, E. L., Jiménez, L., Verwey, W. B., & Clegg, B. A. (2010). Representing serial action and perception. *Psychonomic Bulletin & Review*, 17(5), 603–623.
- Abrahamse, E. L., Ruitenberg, M. F. L., De Kleine, E., & Verwey, W. B. (2013). Control of automated behaviour: Insights from the discrete sequence production task. *Frontiers in Human Neuroscience*, 7(82), 1–16.
- Cohen, J., & Poldrack, R. (2008). Automaticity in motor sequence learning does not impair response inhibition. *Psychonomic Bulletin & Review*, 15(1), 108–115.
- De Kleine, E., & Verwey, W. B. (2009). Representations underlying skill in the discrete sequence production task: Effect of hand used and hand position. *Psychological Research*, 73(5), 685–694.
- Goldberg, G. (1985). Supplementary motor area structure and function: Review and hypotheses. *Behavioral and Brain Sciences*, 8, 567–588.
- Goschke, T., & Bolte, A. (2012). On the modularity of implicit sequence learning: Independent acquisition of spatial, symbolic, and manual sequences. *Cognitive Psychology*, 65(2), 284–320.
- Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., et al. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences*, 22(10), 464–471.
- Jiménez, L., & Méndez, C. (1999). Which attention is needed for implicit learning? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25(1), 236–259.
- Jiménez, L., Méndez, A., Pasquali, A., Abrahamse, E. L., & Verwey, W. B. (2011). Chunking by colors: Assessing discrete learning in a continuous serial reaction-time task. *Acta Psychologica*, 137(3), 318–329.
- Keele, S. W., Ivry, R., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review*, 110(2), 316–339.
- Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, 19(1), 1–32.

- Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: One phenomenon, two approaches. *Trends in Cognitive Sciences*, *10*(5), 233–238.
- Rhodes, B. J., Bullock, D., Verwey, W. B., Averbeck, B. B., & Page, M. P. A. (2004). Learning and production of movement sequences: Behavioral, neurophysiological, and modeling perspectives. *Human Movement Science*, *23*(5), 699–746.
- Romano Bergstrom, J. C., Howard, J. H., & Howard, D. V. (2011). Enhanced implicit sequence learning in college-age video game players and musicians. *Applied Cognitive Psychology*, *26*(1), 91–96.
- Rosenthal, R., Geuss, S., Dell-Kuster, S., Schäfer, J., Hahnloser, D., & Demartines, N. (2011). Video gaming in children improves performance on a virtual reality trainer but does not yet make a laparoscopic surgeon. *Surgical Innovation*, *18*(2), 160–170.
- Schvaneveldt, R. W., & Gomez, R. L. (1998). Attention and probabilistic sequence learning. *Psychological Research*, *61*(3), 175–190.
- Verwey, W. B. (2001). Concatenating familiar movement sequences: The versatile cognitive processor. *Acta Psychologica*, *106*(1–2), 69–95.
- Verwey, W. B. (2010). Diminished motor skill development in elderly: Indications for limited motor chunk use. *Acta Psychologica*, *134*(2), 206–214.
- Verwey, W. B., & Abrahamse, E. L. (2012). Distinct modes of executing movement sequences: Reacting, associating, and chunking. *Acta Psychologica*, *140*, 274–282.
- Verwey, W. B., Abrahamse, E. L., & Jiménez, L. (2009). Segmentation of short keying sequences does not spontaneously transfer to other sequences. *Human Movement Science*, *28*(3), 348–361.
- Verwey, W. B., Abrahamse, E. L., & De Kleine, E. (2010). Cognitive processing in new and practiced discrete keying sequences. *Frontiers in Cognition*, *1*(32).
- Verwey, W. B., Abrahamse, E. L., Ruitenberg, M. F. L., Jiménez, L., & De Kleine, E. (2011). Motor skill learning in the middle-aged: Limited development of motor chunks and explicit sequence knowledge. *Psychological Research*, *75*(5), 406–422.
- West, G. L., Al-Aidroos, N., & Pratt, J. (2013). Action video game experience affects oculo-motor performance. *Acta Psychologica*, *142*(1), 38–42.
- Winer, B. J., Brown, D. R., & Michels, K. M. (1991). *Statistical principles in experimental design*. New York: McGraw-Hill.