Motor sequence learning:

The effect of extended discrete sequence production practice on motor chunking in older adults

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Abstract

Previous research by Verwey (2010) showed that older adults did not use motor chunks to perform keying sequences after practice with the discrete sequence production (DSP) task. The present study examined whether extended practice could contribute to chunking in older adults. DSP practice in this study consisted of two consecutive visits. Participants also performed a task to assess their visuospatial working-memory capacity and a test to determine their speed of information processing. Results showed that older adults already used motor chunks on the first visit to execute the practiced 3-key and 6-key sequence. Furthermore, participants displayed more concatenation between consecutive motor chunks when performing the 6-key sequence on the second visit compared to the first visit, which suggested even more chunking due to the extended practice. However, the visuospatial working-memory capacity and the speed of information processing did not correlate with the chunking indices which measured the degree of chunking.

Introduction

Older adults are less capable of performing ordinary tasks since cognitive functions decrease with age. Almost all cognitive functions (e.g., perception, memory, motor control) deteriorate (Rabbitt, 1997). According to Verhaeghen and Salthouse (1997), the decline of cognitive ability becomes especially apparent after the age of 50. Voelcker-Rehage (2008) performed a literature review on motor-skill learning in older adults, which showed that older adults particularly struggle with fine and complex motor skills. Fine motor skills involve precise movements. This skill becomes apparent when manipulating tools or objects while sitting down which involves control of individual movements. Complex motor skills on the other hand involve higher levels of coordinated movements that require learning and practice. It is not likely that complex motor skills can be mastered in a single training session (e.g., ball sports, dance and martial arts) due to the unpredictable and changing environments in which the person moves (Kraft, Steel, Macmillan, Olson & Merom, 2015). Research regarding motor skills of older adults is important because new insights can possibly be used to improve the lives of older adults. Research may focus on sequential tasks that involve fine movements. Sequential motor skills are an important part of various human motor functions, varying from simple to complex motor activities. Activities such as putting on clothes, driving a car, tying a shoelace, or typing on a laptop computer require some form of sequential motor skills. Much research within the domain of cognitive psychology has been conducted to understand how motor actions are represented and controlled. This kind of research is normally performed by using various experimental tools that generally can be categorized into two main paradigms: "motor adaptation" and "motor sequence learning" (Abrahamse, Ruitenberg, de Kleine & Verwey, 2013). In this paper, the main focus lies on the latter.

Motor sequence learning has been defined as acquiring the skill to quickly and precisely produce a sequence of movements with minimal effort and attentional control (Abrahamse et al., 2013). Learning may take place for various reasons such as explicit instructions, repeated practice, or implicit discovery of sequence regularity. The human capability to obtain sequential motor skills has been an important subject of study in the last decades. As all our actions have some form of sequential structure, researchers are curious about sequenced (goal-directed) actions and want to examine these actions to gain more insight into how people learn new motor behaviors (Abrahamse et al., 2013). One way to examine motor sequence learning is by using the discrete sequence production (DSP) task (Verwey, 2001). This is a method to examine the basic components of more complicated behavioral patterns that underlie human behavior in everyday life. Using this task, the process of learning sequential motor skill can be monitored in a controlled experimental setting. Furthermore, participants can obtain sequential motor skill rapidly with this task. According to Shea and Kovacs (2013), if participants become aware of the structure of the sequence elements, learning of motor sequences can be increased to the point that the whole sequence can be executed in a quick and fluent way, with little or no hesitation between the sequence elements.

In a typical DSP task, the participants place four to eight fingers on the predetermined keys of a computer keyboard. The number of keys used in the task corresponds to the number of placeholders presented on the computer screen (usually in the form of squares). The keys that are used correspond to the specific placeholders in a way that is spatially compatible. When a placeholder illuminates, the participant presses the spatially compatible key as quickly as possible, which in turn causes the next stimulus to be presented. Again, a placeholder lights up and the participant rapidly reacts to this stimulus. Two fixed sequences comprised of 3-7 stimuli are applied in a typical DSP task. Participants can react to the stimuli by pressing the corresponding keys on a computer keyboard. The DSP task consists of two phases. In the practice phase, the participants get the opportunity to learn the motor sequences as each sequence is typically presented 500 - 1000 times. Through training, participants develop so-called motor chunks: responses can be selected and executed as if they are a single response (Abrahamse et al., 2013). After the practice phase, the test phase follows in which the reaction times (RTs) obtained with the learned (familiar) sequences are compared to the RTs obtained with new (unfamiliar) sequences.

According to Verwey and Eikelboom (2003), longer sequences are divided into multiple motor chunks due to the limited length of a single motor chunk. A so-called concatenation point (i.e., a relatively high RT after sequence initiation) is believed to indicate the transition from one motor chunk to the next (e.g., Verwey, Abrahamse & de Kleine, 2010).

Based on research with the DSP task, the Dual Processor Model of sequence learning has been proposed (see Verwey, 2001; Abrahamse et al., 2013). This model describes that two different processors are operating during sequence learning: the cognitive processor and the motor processor. The amount of input from these two processors to the performance of sequencing skill varies with the degree of training, which leads to specific modes of sequence performance. At the beginning of DSP practice, the motor sequence is performed in the so-called reaction mode. Pressing each key of the sequence is not influenced by the other key presses of the same sequence in this mode. The cognitive processor loads the individual sequence elements in the motor buffer and translates these elements into the suitable response. The motor processor is responsible for the production of each key press response. When participants are trained extensively to execute a discrete motor sequence, they perform this sequence in the chunking mode. In this mode, it is not necessary anymore for participants to separately select, load, and execute all the distinctive elements of the motor sequence since participants can automatically perform the entire motor sequence on the basis of the first stimulus that indicates which of the sequences should be carried out. In this case, a motor chunk is loaded in the motor buffer instead of loading separate sequence elements. Once the motor chunk is loaded, the motor sequence can be performed very quickly (Verwey, 2001). Verwey and Dronkert (1996) described a motor chunk as a short sequence of consecutive responses that are represented in a single memory representation. The motor sequence can be prepared beforehand and performed at high speed. Thus in this case, on the basis of the first stimulus (and the first accompanying key press), the participants can perform the entire key press sequence (without paying any attention to the remaining stimuli) as if it was a single response. In other words, the chunking behavior can be seen in the RTs of the key presses; RTs of key presses after the first are generally short.

Discrete keying sequences can also be performed in a third mode. Verwey (2003) demonstrated that participants execute the sequences at an intermediate speed (i.e., the associative mode) when switching from slow to fast sequence production. In this mode, succeeding responses are primed by the preceding reactions. However, the processing of the stimulus is still needed for the actual task execution. Sequence execution in the associative mode takes place when participants are prevented from using the chunking mode (Verwey & Abrahamse, 2012).

Verwey (2010) examined motor skill development in older adults by using the DSP task. He investigated whether older adults (aged 75-88) make a transition from the reaction mode to the chunking mode, in terms of executing the motor sequences, like young adults do (aged 18-28). 3-Key sequences and 6-key sequences were used in this study. Participants practiced the two sequences over six practice blocks. It was randomly determined whether the 3-key or the 6-key sequence had to be performed during the practice blocks. They performed 24 six-key sequences and 24 three-key sequences per practice block. For each sequence, there were 144 trials per sequence in total. One of the main results was that most older adults stayed in reaction mode throughout the entire practice phase of the experiment and did not switch to chunking mode (unlike the young adults). The older adults only displayed associative learning which can be seen in the RT improvements because participants developed associations between responses in a familiar sequence. Thus, the older adults still benefitted from practice even though they did not use motor chunks.

Verwey, Abrahamse, Ruitenberg, Jiménez & de Kleine (2011) found in their DSP study with middle-aged participants (aged 55-62) that motor chunks were less developed after practice with a 3-key and a 6-key sequence. Only associative learning was observed in that RTs moderately declined gradually over the key presses. There was no sign of motor chunking as a clear distinction between the slow RT of the first key press and the fast RTs of subsequent key presses was not observed in the 3-key or 6-key sequence performance.

In the above-mentioned studies, older participants showed few indications of motor chunk use. Verwey (2010) concluded that the older adults still performed the motor sequences as series of individual key presses after practice, instead of executing the sequences as an integrated pattern (i.e., motor chunks). To examine whether older adults would show sequence-specific improvements to the point of motor chunking after extended practice, the present study focused on whether older adults develop motor chunks if participants practiced the DSP task for a longer time than in the previous studies. It is possible that the development of motor chunks is relatively slow among older adults compared to younger adults and that motor chunking may only be visible after extended practice with the motor sequences.

A motor learning study in which there was clearly an effect of age on the motor performance, was the study of Rodrigue, Kennedy and Raz (2005). Participants performed a mirror-tracing task in which they traced a six-pointed star with a stylus. However, participants could only see a mirror-inverted image of the star. There were five blocks of five trials in total that were spread over 3 consecutive days (block 1 on day 1; block 2 & 3 on day 2; block 4 & 5 on day 3). Results showed that younger adults (aged 28–36) and middle-aged adults (aged 45–56) showed their optimum motor performance (tracing speed) by the end of day 2, whereas older adults (aged 62–82) showed their optimum tracing speed on day 3. Just as in the above-mentioned study, older adults might perform the DSP task better after more training. They may need extended practice to develop motor chunks. One possible explanation is that associations may develop at a slower pace compared to younger adults (Naveh-Benjamin, 2000). In this context, older adults might only develop motor chunks after more DSP training which can be seen in the relatively slow RT of the first key press followed by significantly faster RTs of the subsequent key presses.

Since working memory can be measured in various ways, it would be interesting to see whether other working memory processes (besides processes involved in motor sequence execution) are associated with sequence performance, such as the visuospatial working-memory and the speed of information processing. A Visual Array Comparison (VAC) task similar to the visuospatial working-memory task used by Luck and Vogel (1997; experiment 1) and a digit-symbol substitution test in the Wechsler Adult Intelligence Scale—Revised (WAIS-R; Wechsler, 1981) are used to assess these working memory processes. Participants who have a large visuospatial working-memory capacity and the capacity to process information rapidly might show more explicit chunking behavior (i.e., higher chunking indices) than participants with lower capacities in that respect. Thus, it is expected that the VAC score and the digit-symbol substitution score are associated with chunking.

As mentioned earlier, older adults in the study of Verwey (2010) did not use motor chunks when performing the keying sequences. The main question of the present study was whether extended DSP practice could contribute to chunking in older adults. DSP practice in this study consisted of two consecutive visits. The first visit was comparable to the DSP practice in Verwey (2010). The second visit was intended to see what would happen if older adults received extra DSP practice. In order to answer the main question, the following hypothesis was formulated: Older adults do not show chunking behavior yet on visit 1. However, motor chunks will eventually be developed in older adults after receiving extended practice on visit 2. Moreover, it was expected that the visuospatial working-memory capacity and the speed of information processing could predict chunking behavior. This led to the second hypothesis: The higher the VAC score and the digit-symbol substitution score are, the more chunking participants display.

Methods

Subjects

Eighteen older adults from the region of Twente participated in the experiment (mean age 79, range 74-85, 5 women). Selection criteria for the older adults were that the participants were at least 74 years and at most 85 years of age, were right-handed, were not color blind, and were healthy. Specifically, they did not suffer from severe motor impairments (e.g., use of wheelchair, severely restricted in the use of arms or fingers). Moreover, older adults were excluded from the experiment when they suffered from neurological disorders, severe rheumatoid arthritis, or muscle disorders. As a compensation for their participation, each participant received a fee of 35 Euros (with travel allowance, if necessary). The ethics committee of University of Twente approved this experiment.

Apparatus

The E-prime 2.0 software was used for stimulus presentation and data collection. This software ran on a personal computer (located in the laboratory of University Twente) with an Intel Core i7-3770 CPU (3.40 GHz) processor. Only the basic and essential Windows 7 services were switched on to allow reaction times to be measured accurately. Stimuli were displayed on a 22 inch LG Flatron E2210 monitor.

Procedure

Before the participants visited the laboratory, they received an information letter about the experiment that outlined that the experiment required two visits (on two consecutive days) to the laboratory. They also received an informed consent, an activity questionnaire, and the Edinburgh Handedness Inventory form (Oldfield, 1971) by mail. They were instructed to fill in the latter two documents at home before the first visit. The informed consent was signed during the first lab visit.

On the day of the first visit, the Montreal Cognitive Assessment (MoCA; Nasreddine, 2004) was administered at the beginning. The MoCA is a cognitive screening tool for mild cognitive impairment. All participants scored sufficiently on this test (thus no participants were excluded from this study). Then, the participant began with the DSP practice phase by performing the first 3 practice blocks. In each practice block, a fixed 6-key sequence and 3-key sequence were presented 24 times. The 6-key sequence and 3-key sequence were displayed in a random order. In the middle of each practice block there was a break that lasted for 40 seconds. After completion of each practice block there was a 2-minute break. During this break the error percentage and mean RT in ms were displayed on the screen. Moreover, participants indicated their fatigue level on a (ad hoc) fatigue score form during 4 fixed moments between the practice blocks and performed the digit-symbol substitution test (DSST; Wechsler, 1981) after the 6th practice block, which measured the speed of information processing. The participant completed the first visit by performing the last 3 practice blocks (practice block 7-9) and indicating the 4th fatigue score (see table 1).

On the second visit, the participant started with the Visual Array Comparison (VAC) task which is a modified version of the visuospatial working-memory task published by Luck and Vogel (1997; experiment 1). In the VAC task, 2 to 8 stimuli were presented in each trial, whereas 1 to 12 stimuli were displayed in the original task by Luck and Vogel. Again, participants indicated their fatigue level on 4 fixed occasions between the practice blocks. Also, the explicit knowledge questionnaire was administered after the last practice block. Just like the first visit, participants performed 9 practice blocks in total (i.e., 216 trials per sequence). At the end of the second visit, participants performed the test phase. This test phase consisted of a familiar and an unfamiliar block (see table 1).

Table 1

Overview of tasks

Visit 1	**Visit 2**
MOCA	Fatigue score 5
Fatigue score 1	VAC task
3x DSP practice block	3x DSP practice block
Fatigue score 2	Fatigue score 6
10 minute break	10 minute break
3x DSP practice block	3x DSP practice block
Fatigue score 3	Fatigue score 7
Digit-symbol substitution test	5 minute break
5 minute break	3x DSP practice block
3x DSP practice block	Fatigue score 8
Fatigue score 4	Explicit knowledge questionnaire
	1x DSP test block

Tasks and Questionnaires

Activity questionnaire

There were two documents that had to be filled in by the participants before their first visit: the Edinburgh Handedness Inventory form (Oldfield, 1971) and the activity questionnaire. The activity questionnaire consisted of questions about personal information and physical activity (e.g., questions about education, work, health, diseases, sports, and manual activities).

Fatigue score form

At moments between the practice blocks of visit 1 and 2, participants indicated their level of fatigue at that moment by placing a circle around a number on the 0-10 scale, with 0 indicating "no fatigue" and 10 indicating "high level of fatigue".

Digit-symbol substitution test

Participants completed the digit-symbol substitution test (Wechsler, 1981) that consisted of two parts on visit 1. The first part of the digit-symbol substitution test required participants to write down as many symbols as possible that corresponded with number 1 to 9 in a 90 second period. During this part, participants could look at the table with the correct digit-symbol correspondences while writing down the symbols. The second part of this task required the participants to write down the symbols corresponding to the numbers without looking at the digit-symbol table. The Digit-symbol substitution score is equivalent to the amount of symbols written in the 90 seconds time period and indicates the information processing speed of a participant.

Explicit knowledge questionnaire

The explicit knowledge questionnaire was administered at the end of visit 2 right before the test phase. At that moment, participants had performed 18 practice blocks in total (each visit had 9 practice blocks), which is equivalent to 432 practice trials per sequence. Question 1A of this questionnaire asked them to write down the key press letters of each performed sequence (from left to right) and also indicate the certainty level of the given sequences being correct on a scale from 1 to 4 (with 1: "absolutely not sure"; 4: "absolutely sure"). Question 1B then followed that required the participants to point at the placeholders presented on the screen and indicate in which order the placeholders illuminated for each sequence. Again, the certainty level was given on a scale from 1 to 4. Furthermore, a table with 12 different 6-key sequences and a table with 12 different 3-key sequences were given in question 2. In each table one sequence was presented correctly and participant had to indicate which 6-key and 3-key sequence they performed during the practice blocks. The certainty level could be given on a scale from 1 to 10 (with 1: "uncertain"; 10: "certain"). The remaining questions in this questionnaire asked about the strategy of how the participants remembered/recognized their sequences in the previous three questions (question 3) and whether they found the two sequences to be equally easy to perform. They also had to indicate which sequence was easier to perform and give a reason for this when they indicated that one kind of key sequence was easier to execute than the other (question 4).

Explicit knowledge scores were equivalent to the amount of elements correctly indicated from the start of the sequence till the first mistake (e.g., when in the given 6-key sequence only the third element is incorrect, then the score is 2) and the number of times they correctly pointed out which sequences they performed. They had to choose the performed 3-key and 6-key sequence from a list. For question 1A and 1B, the score ranged from 0 to 9. The maximum score could be obtained by correctly indicating the entire 6-key and 3-key sequence. For question 2, the score ranged from 0 to 2. If the participant recognized the correct 6-key and 3-key sequence in the sequence lists, then a score of 2 was given. The final explicit knowledge score was equal to the addition of the scores of question 1A, 1B and 2 and it ranged from 0 to 20. These scores and answers of the explicit knowledge questionnaire are not reported in this study.

<u>DSP practice phase</u>

On the computer screen, six black 28 x 28 mm placeholders were presented horizontally in the middle of the screen against a white background. There was a 14 mm gap between the placeholders with the exception of a 56 mm gap between the third and fourth placeholder. In the middle of the 56 mm gap, the letter "H" was presented that resembled the positions of the keyboard keys (i.e., DFG and JKL) on the left and right side of the H key. Participants had to place their ring finger, middle finger and index finger of their left hand on the keys DFG and their index finger, middle finger and ring finger of their right hand on the keys JKL and were instructed to rest the fingers on these keys when not pressing a key. The moment a placeholder lit up (i.e., turned green), participants pressed the corresponding (spatially compatible) key (i.e., D, F, G, J, K or L) on a regular computer keyboard. The green color in the placeholder changed back to the white background color when the participant pressed the key correctly, and after that, the next placeholder lit up and the correct key had to be pressed again. This continued until the entire sequence was performed. A small pause followed after execution of an entire sequence; the computer screen turned white entirely for 1250 ms to indicate completion of the 3-key or 6-key sequence. Then the placeholders were displayed again for 1000 ms and the first stimulus of the following sequence was presented. Pressing a key too early during the pause resulted in an error message "Too early" (in Dutch) for 1500 ms. Pressing a false key resulted in the message "Wrong" (in Dutch) for 1500 ms. In this case, the ongoing sequence was interrupted and the next sequence had to be executed after a display of an empty screen for 1000 ms. If a stimulus was presented and no key was pressed in the 20-second period after initial presentation, an error message appeared "Not responded" (in Dutch) for 1500 ms.

After the first stimulus of a sequence was presented, every subsequent stimulus of that sequence was directly displayed when the correct prior key was pressed which means that there was a zero response stimulus interval (RSI). The interkey intervals (IKI) were equivalent to the response times. The stimuli of the DSP task (i.e., placeholders lighting up) were displayed in a fixed sequence of three or six (S_1-S_3 and S_1-S_6, respectively) and thus a fixed sequence of three or six key presses (R_1–R_3 and R_1–R_6, respectively) had to be performed. The term "trial" stands for performing a complete 3-key or 6-key sequence. RT_n indicates the time between stimulus *n* and response *n* and can be seen as the response time. There were six different 6-key and six different 3-key sequences in total. See the appendix for the full list of the performed sequences of each participant. The ring finger, middle finger and index finger of both hands were counterbalanced across the six keys. For example, one participant performed the sequence FKGDJL and the next participant performed the sequence LGJFKD (each key is shifted to the right).

DSP test phase

The test phase consisted of a familiar and an unfamiliar block. During the familiar block of the test phase, each of the two sequences (a 6-key and 3-key sequence that were also presented during the practice blocks of visit 1 and 2) was displayed 12 times in random order. Twelve random 3-key sequences and 12 random 6-key sequences were shown during the unfamiliar block of the test phase. The two test blocks were separated by a break of 40 seconds and the order of the familiar and unfamiliar test blocks was counterbalanced across the participants.

Visual Array Comparison (VAC) task

The VAC task was performed at the beginning of visit 2. The VAC task was a modified version of the visuospatial working-memory task used by Luck and Vogel (1997; experiment 1). Participants were asked to fixate on a cross that was presented in the middle of the screen for 900 ms. Then a sample array of colored squares was displayed very shortly (100 ms) on the screen. A blank screen followed for 900 ms and then the test array was presented for 2000 ms in which the same amount of squares (as in the sample array) was presented in exactly the same locations on the screen. One of the squares was circled and participants were asked to decide whether the circled square had the same color as the square in the sample array (which was the case in half of the trials) by pressing the "A" key (i.e., same color) with the left index finger or the "L" key (i.e., different color) with the right index finger. After each trial, a feedback screen appeared that indicated whether the response was correct or not. By pressing the space bar on the keyboard the participant continued with the next trial. Each array consisted of 2, 4, 6 or 8 colored squares and each array size occurred 30 times in random order. It was also randomly decided which of the seven colors (white, black, yellow, green, purple, blue, and red) each square had. It was possible that several squares got the same color in an array. The ratio in which the same arrays and different arrays were presented was 1:1 and they appeared in random order. The VAC score that indicated the memory capacity (K) was calculated by applying the formula $(K) = S(H - F)$ used by Vogel and Machizawa (2004), where S is the size of the array, H is the observed hit rate, and F is the false alarm rate. Just like in the study of Bo, Borza and Seidler (2009) that used the same formula, the K value was calculated for each array size and the mean K was taken across all array sizes to indicate the visuospatial working-memory capacity of each participant.

Design and analyses

In this study, it was predicted that during extended practice RT_2 and RT_3 of the 3-key sequence and RT_2, RT_3, RT_4, RT_5, and RT_6 of the 6-key sequence would decrease more across the blocks than RT_1 of that respective sequence making the difference between RT_1 and the mean

RT of the subsequent key presses of the 3-key or 6-key sequence bigger over time, which could be considered as a sign of motor chunk development. To examine how much chunking increased for the 3-key and 6-key sequence during the practice phase of the first visit (i.e., across practice block 1 to 9) and the second visit (i.e., across practice block 11 to 18), four separate variables were calculated: 3-key chunking increase on visit 1 (i.e., "3-key CI_1"), 6-key chunking increase on visit 1 (i.e., "6-key CI_1"), 3-key chunking increase on visit 2 (i.e., "3-key CI_2"), and 6-key chunking increase on visit 2 (i.e., "6-key CI_2").

To compute the 3-key CI_1, the mean of RT_2 and RT_3 (pooled together) in practice block 1 was subtracted from the mean RT_1 in practice block 1. This 3-key initiation-execution difference was also calculated for practice block 9. The 3-key CI_1 was then acquired by subtracting the 3-key initiation-execution difference of practice block 1 from the 3-key initiation-execution difference of practice block 9. The 6-key CI_1 was calculated by subtracting the mean of RT_2, RT_3, RT_4, RT_5, and RT_6 (i.e., *mean execution time*) from the mean RT_1 (i.e., *mean initiation time*) in practice block 1 and 9. This 6-key initiation-execution difference of practice block 1 was then subtracted from the 6-key initiation-execution difference of practice block 9.

The 3-key CI_2 and 6-key CI_2 were calculated in a similar way as described above except RTs of practice block 11 and 18 were used in the calculation. When calculating the CI_2, it was decided to subtract the initiation-execution RT difference of block 11 (instead of block 10: the first practice block of visit 2) from that of block 18 to get more accurate estimate of chunking increases. As participants already had experience with the DSP task on visit 1, it was expected that they could complete the practice blocks relatively fast almost right away. But participants might have to get used to the task first ("warm-up effect") in the very beginning of visit 2 causing each key press to have high RTs and the initiation-execution RT difference of block 10 to be relatively small. In turn, this might result in an inaccurate estimate of chunking increase. As participants already were exposed to the DSP task on visit 1, it was believed that after getting used to the task (in practice block 10), practice block 11 would be more accurate in capturing the actual DSP task performance expected at the beginning of visit 2. For this reason, it was decided to exclude practice block 10, when examining RTs of visit 2 using various ANOVAs.

To measure the degree of chunking as in the study of Verwey (2010), several chunking indices were computed: the 3-key chunking index, the 6-key chunking index and the general chunking index. As Bo, Borza and Seidler (2009) found that older adults used motor chunks that were significantly shorter in length compared to young adults, older adults may be more inclined to use motor chunks when performing 3-key sequences than 6-key sequences. This is why separate chunking indices were calculated for the 3-key and the 6-key sequence. The 3-key chunking index was calculated by subtracting the mean of RT_2 and RT_3 from the mean RT_1. This difference in RT was called the 3-key initiation-execution difference (IED) and was determined for the familiar 3-key sequence and the unfamiliar 3-key sequence. Then, the unfamiliar 3-key IED was subtracted from the familiar 3-key IED. The 6-key chunking index was obtained in the same way, except the mean of RT_2, RT_3, RT_4, RT_5, and RT_6 was subtracted from the mean RT_1 of the 6-key sequence (i.e., the 6-key IED). This chunking index was then acquired by subtracting the unfamiliar 6-key IED from the familiar 6-key IED. Lastly, the general chunking index was computed by taking the mean of the 3-key and 6-key chunking index.

Repeated measures analyses of variance (ANOVAs) were used to analyze the mean RTs of each key press of the 3-key and 6-key sequence. This was carried out for each participant and practice block or test block. Sequences in which a key press error was made were excluded from the analyses. Effect sizes are indicated with partial eta-squared ($p\eta^2$). Similar to the study of Verwey (2010), sequences of the test phase were excluded from analyses in case their execution time surpassed the mean sequence execution time greater than 2.5 times standard deviation of the mean sequence execution time of the particular test block (familiar or unfamiliar test block), in order to increase the chance to find significant effects in the test phase and to allow more accurate comparison between the results of this study (e.g., general chunking indices) and those of Verwey (2010). This procedure was performed separately for the 3-key and 6-key sequences in the familiar and unfamiliar test block for each participant. As a result of this, 1.2% of the data across all participants was excluded from analyses. Furthermore, visit 1 and visit 2 were analyzed separately to determine the Block x Key interaction effect of each visit. This way, the chunking increase on day 1 could be compared to that on day 2.

Results

Practice phase

The mean RTs of the 3-key sequence across the practice blocks of visit 1 (i.e., block 1 to 9) and visit 2 (i.e., block 10 to 18) are presented in figure 1. All key presses of the 3-key sequence seemed to improve across practice blocks 1 to 9 and across practice blocks 10 to 18, especially key press 2 and 3. RTs were subjected to ANOVAs to test these observations.

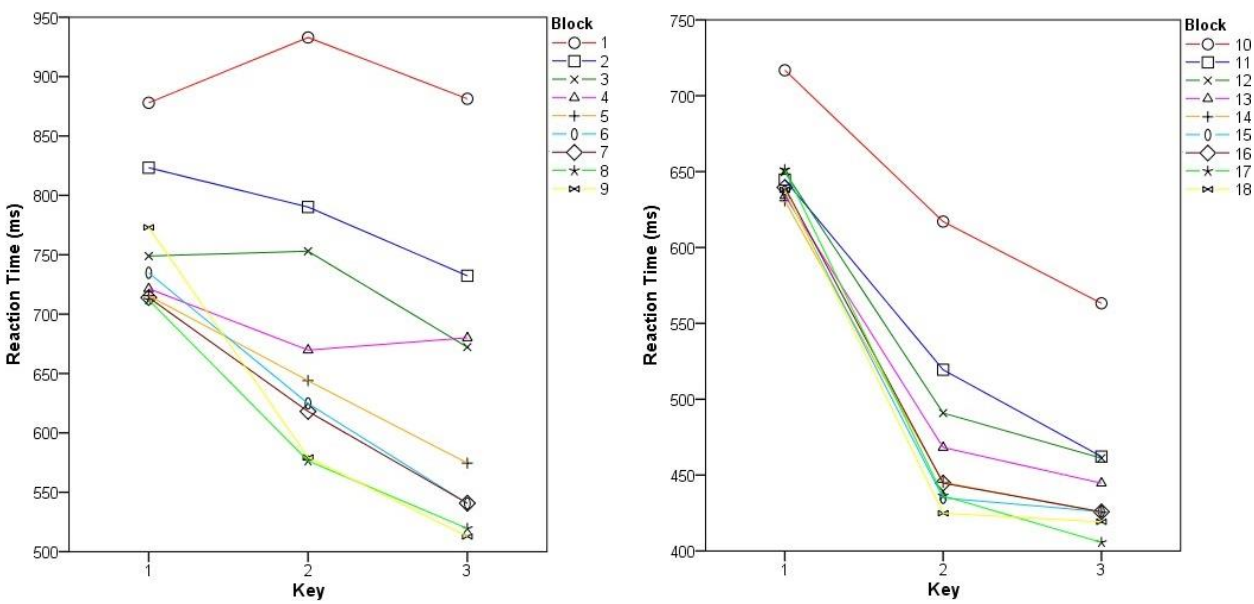
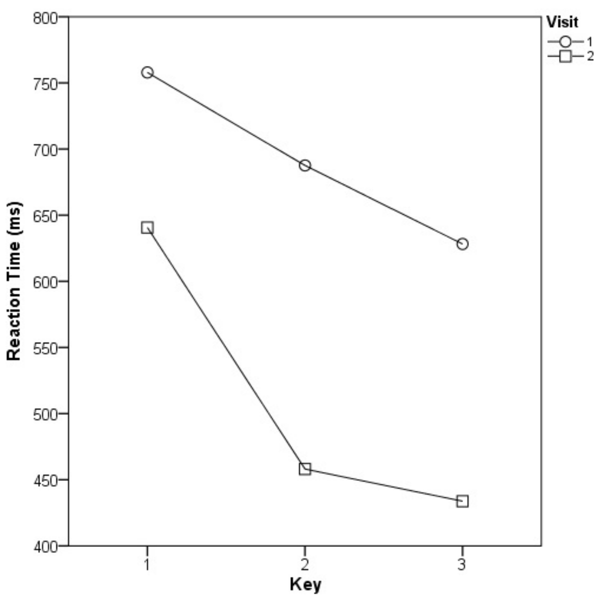


Figure 1. Mean RTs (in milliseconds) per key of the 3-key sequence in each practice block of visit 1 (block 1 – 9) and visit 2 (block 10 – 18).

3-key sequence performance on visit 1 (block 1 to 9)

A repeated measures ANOVA with Block (9; practice blocks 1 – 9) and Key (3; key 1 – 3) as within-subject factors was used. A main effect of Key indicated that there was a significant difference between the RTs of the 3 key presses on visit 1, $F(2, 34) = 6.442$, $p = .004$, $p\eta^2 = .275$. As can be seen in figure 2, RT_2 and RT_3 (688 ms and 628 ms, respectively) were faster than RT_1 (758 ms). A main effect of Block showed that the mean RT of key press 1 to 3 pooled together decreased across the practice blocks of visit 1 (mean RT in block 1 was 897 ms and it decreased to 622 ms in block 9), $F(8, 136) = 21.600$, $p < .001$, $p\eta^2 = .560$. Moreover, a Block x Key interaction effect, $F(16, 272) = 3.128$, $p < .001$, $p\eta^2 = .155$, showed that not only did RTs varied across the key presses, but the RT differences also varied across practice blocks 1 to 9. As can be seen in figure 1, the RT difference between the initiation and the execution of the 3-key sequence (i.e., RT_1 subtracted by the *mean of* RT_2 *and* RT_3) became more and more apparent over the practice blocks. The mean initiation-execution difference went from -29 ms in block 1 to 227 ms in block 9 and therefore the mean change of initiation-execution difference (i.e., "3-key CI_1") was 256 ms. This result together with figure 1 suggested that older participants already used motor chunks to perform the 3-key sequence during visit 1. Also, a repeated measures ANOVA with Block (9; practice blocks 1 – 9) and Key (2; key 2 & 3) as within-subject factors showed that RT_3 was significantly faster than RT_2 on visit 1, $F(1, 17) = 4.932$, $p = .040$, $p\eta^2 = .225$.

A repeated measures ANOVA with Block (9; practice blocks 1 – 9) as a within-subject factor conducted on each key press showed a main effect of Block on RT_1 which indicated that RT_1 varied across practice blocks 1 to 9, $F(8, 136) = 2.980$, $p = .004$, $p\eta^2 = .149$. This was also the case for RT_2, $F(8, 136) = 22.824$, $p < .001$, $p\eta^2 = .573$, and RT_3, $F(8, 136) = 15.169$, $p < .001$, $p\eta^2 = .472$. As can be seen in figure 1, RT_2 and RT_3 generally decreased gradually across the practice blocks, which was in contrast to RT_1. The mean of RT_2 and RT_3 reduced from 907 ms in block 1 to 546 ms in block 9.



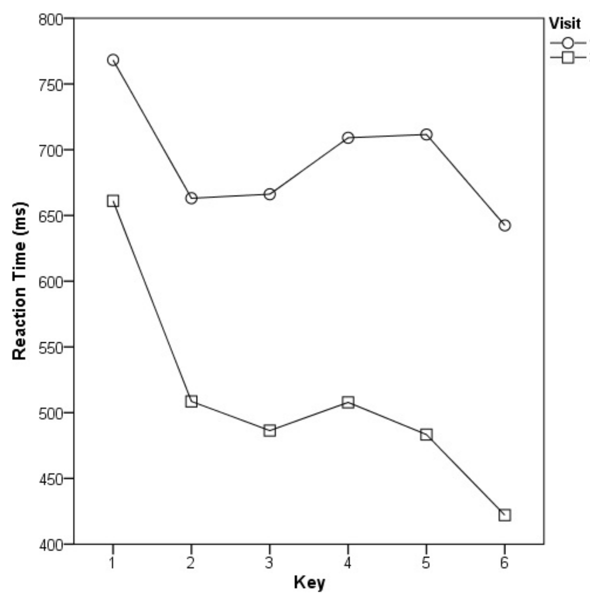


Figure 2. Mean RTs (in milliseconds) per key of the 3-key and 6-key sequence on each visit.

<u>3-key sequence performance on visit 2 (block 11 to 18)</u>

A repeated measures ANOVA was conducted with Block (8; practice blocks 11 – 18) and Key (3; key 1 – 3) as within-subject factors. A main effect of Key indicated that there was a significant difference between the RTs of the 3 key presses on visit 2 (Block 11 to 18), $F(2, 34) = 24.643$, $p < .001$, $p\eta^2 = .592$. As can be seen in figure 2, RT_2 and RT_3 (458 ms and 434 ms, respectively) were faster than RT_1 (641 ms). A main effect of Block showed that the mean RT of key press 1 to 3 pooled together decreased across the practice blocks of visit 2 (mean RT in block 11 was 542 ms and it decreased to 494 ms in block 18), $F(7, 119) = 5.100$, $p < .001$, $p\eta^2 = .231$. Furthermore, the Block x Key interaction effect was not significant, $F(14, 238) = 1.690$, $p = .058$, $p\eta^2 = .090$, which indicated that the RT differences between key presses did not vary significantly over practice blocks 11 to 18. As can be seen in figure 1, the RT difference between the initiation and the execution of the 3-key sequence (i.e., RT_1 subtracted by the *mean of* RT_2 *and* RT_3) seemed to become somewhat greater over the practice blocks. The mean initiation-execution difference went from 154 ms in block 11 to 216 ms in block 18 and therefore the mean change of initiation-execution difference (i.e., “3-key CI_2”) was 62 ms. A repeated measures ANOVA with Visit (2; visit 1 & 2) as a within-subject factor showed that the 3-key chunking increase of visit 1 was different from that of visit 2, $F(1, 17) = 4.602$, $p = .047$, $p\eta^2 = .213$. In other words, the change of initiation-execution difference of visit 2 was less apparent than that of visit 1 (62 ms vs. 256 ms, respectively). Also, a repeated measures ANOVA with Block (8; practice blocks 11 – 18) and Key (2; key 2 & 3) as within-subject factors showed that RT_3 was significantly faster than RT_2 on visit 2, $F(1, 17) = 5.547$, $p = .031$, $p\eta^2 = .246$.

A repeated measures ANOVA with Block (8; practice blocks 11 – 18) as a within-subject factor conducted on each key press showed no main effect of Block on RT_1 which indicated that RT_1 did not vary across practice blocks 11 to 18, $F(7, 119) = .209$, $p = .983$, $p\eta^2 = .012$. However, RT_2 varied across the practice blocks, $F(7, 119) = 9.969$, $p < .001$, $p\eta^2 = .370$, as well as RT_3, $F(7, 119) = 2.731$, $p = .012$, $p\eta^2 = .138$. As can be seen in figure 1, RT_2 and RT_3 generally decreased gradually across the practice blocks which was in contrast to RT_1. The mean of RT_2 and RT_3 pooled together reduced from 491 ms in block 11 to 422 ms in block 18. A repeated measures ANOVA with Visit (2; visit 1 & 2) as a within-subject factor showed that the RT decrease of key press 2 and 3 (pooled together) on visit 2 was less apparent compared to that of visit 1 (69 ms vs. 361 ms, respectively), $F(1, 17) = 36.909$, $p < .001$, $p\eta^2 = .685$.

<u>6-key sequence performance on visit 1 (block 1 to 9)</u>

A repeated measures ANOVA was conducted with Block (9; practice blocks 1 – 9) and Key (6; key 1 – 6) as within-subject factors. A main effect of Key indicated that there was a significant difference between the RTs of the 6 key presses on visit 1, $F(5, 85) = 2.905$, $p = .018$, $p\eta^2 = .146$. As can be seen in figure 2, RT_2 (663 ms), RT_3 (666 ms), RT_4 (709 ms), RT_5 (712 ms), RT_6 (642 ms) were faster than RT_1 (768 ms). A main effect of Block showed that the mean RT of key press 1 to 6 pooled together decreased across the practice blocks of visit 1 (mean RT in block 1 was 924 ms and it decreased to 612 ms in block 9), $F(8, 136) = 20.718$, $p < .001$, $p\eta^2 = .549$. Moreover, a Block x Key interaction effect, $F(40, 680) = 4.145$, $p < .001$, $p\eta2 = .196$, showed that not only did RTs vary across the key presses, but the RT differences also varied across practice blocks 1 to 9. As can be seen in figure 3, the RT difference between the initiation and the execution of the 6-key sequence (i.e., RT_1 subtracted by the *mean of* RT_2, RT_3, RT_4, RT_5 *and* RT_6) became more and more apparent over the practice blocks. The mean initiation-execution difference went from -90 ms in block 1 to 171 ms in block 9 and therefore the mean change of initiation-execution difference (i.e., "6-key CI_1") was 261 ms. A repeated measures ANOVA with Sequence (2; 3-key & 6-key) as a within-subject factor showed that the chunking increase on visit 1 did not seem to vary across the 3-key and 6-key sequence, $F(1, 17) = .003$, $p = .957$, $p\eta^2 < .001$ (256 ms and 261 ms, respectively). These results together with figure 3 suggested that older participants also used motor chunks to perform the 6-key sequence during visit 1. When only the RTs of the key presses after sequence initiation were analyzed (RT_2 to RT_6) by conducting a repeated measures ANOVA with Block (9; practice blocks 1 – 9) and Key (5; key 2 – 6) as within-subject factors, the main effect of Key was not significant, $F(4, 68) = 1.681$, $p = .165$ $p\eta^2 = .090$. According to figure 2, RT_4 and RT_5 were somewhat higher than RT_2, RT_3 and RT_6.

A repeated measures ANOVA with Block (9; practice blocks 1 – 9) as a within-subject factor conducted on each key press showed a main effect of Block on RT_1 which indicated that RT_1 varied across practice blocks 1 to 9, $F(8, 136) = 2.095$, $p = .040$, $p\eta^2 = .110$. This was also the case for RT_2, RT_3, RT_4, RT_5 and RT_6, $Fs(8, 136) > 10.626$, $ps < .001$, $p\eta^2 > .385$. As can be seen in figure 3, RT_2 to RT_6 decreased gradually across the practice blocks. However, this phenomenon could not be seen in RT_1. The mean of RT_2, RT_3, RT_4, RT_5 and RT_6 pooled together reduced from 939 ms in block 1 to 584 ms in block 9.

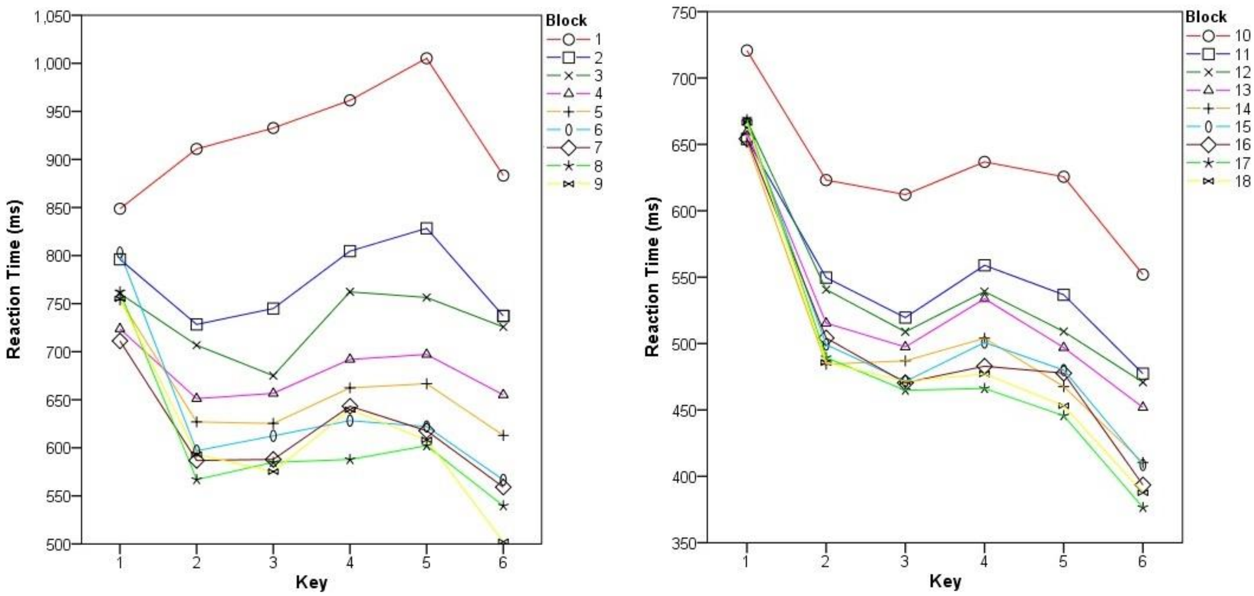


Figure 3. Mean RTs (in milliseconds) per key of the 6-key sequence in each practice block of visit 1 (block 1 – 9) and visit 2 (block 10 – 18).

<u>6-key sequence performance on visit 2 (block 11 to 18)</u>

A repeated measures ANOVA was conducted with Block (8; practice blocks 11 – 18) and Key (6; key 1 – 6) as within-subject factors. A main effect of Key indicated that there was a significant difference between the RTs of the 6 key presses on visit 1, $F(5, 85) = 8.452$, $p < .001$, $p\eta^2 = .332$. As can be seen in figure 2, RT_2 (509 ms), RT_3 (486 ms), RT_4 (508 ms), RT_5 (483 ms), RT_6 (422 ms) were faster than RT_1 (661 ms). A main effect of Block showed that the mean RT of key press 1 to 6 pooled together decreased across the practice blocks of visit 2 (mean RT in block 11 was 549 ms and it decreased to 490 ms in block 18), $F(7, 119) = 6.206$, $p < .001$, $p\eta^2 = .267$. Moreover, a Block x Key interaction effect, $F(35, 595) = 1.838$, $p = .003$, $p\eta 2 = .098$, showed that not only did RTs varied across the key presses, but the RT differences also varied across practice blocks 11 to 18. As can be seen in figure 3, the RT difference between the initiation and the execution of the 6-key sequence (i.e., RT_1 subtracted by the *mean of* RT_2, RT_3, RT_4, RT_5 *and* RT_6) became more and more apparent over the practice blocks. The mean initiation-execution difference went from 126 ms in block 11 to 211 ms in block 18 and therefore the mean change of initiation-execution difference (i.e., “6-key CI_2”) was 85 ms. A repeated measures ANOVA with Visit (2; visit 1 & 2) as a within-subject factor showed that the 6-key chunking increase of visit 1 was different from that of visit 2, $F(1, 17) = 8.179$, $p = .011$, $p\eta^2 = .325$. In other words, the change of initiation-execution difference of visit 2 was less apparent than that of visit 1 (85 ms vs. 261 ms, respectively). Furthermore, a repeated measures ANOVA with Sequence (2; 3-key & 6-key) as a within-subject factor showed that the chunking increase on visit 2 did not seem to vary significantly across the 3-key and 6-key sequence, $F(1, 17) = .823$, $p = .377$, $p\eta2 = .046$ (62 ms and 86 ms, respectively). When only the RTs of the key presses after sequence initiation were analyzed (RT_2 to RT_6) by conducting a repeated measures ANOVA with Block (8; practice blocks 11 – 18) and Key (5; key 2 – 6) as within-subject factors, there was a significant main effect of Key, $F(4, 68) = 2.670$, $p = .039$, $p\eta^2 = .136$. According to figure 2, RT_6 was faster than RT_2, RT_3, RT_4 and RT_5.

A repeated measures ANOVA with Block (8; practice blocks 11 – 18) as a within-subject factor conducted on each key press showed no main effect of Block on RT_1 which indicated that RT_1 did not vary across practice blocks 11 to 18, $F(7, 119) = .179$, $p = .989$, $p\eta^2 = .010$. However, RT_2, RT_4, RT_5 and RT_6 varied across the practice blocks, $Fs(7, 119) \geq 4.259$, $ps < .001$, $p\eta^2 \geq .200$. RT_3 varied marginally across the practice blocks, $F(7, 119) = 2.081$, $p = .051$, $p\eta^2 = .109$. As can be seen in figure 3, RT_2 to RT_6 generally decreased across the practice blocks which was in contrast to RT_1. The mean of RT_2, RT_3, RT_4, RT_5 and RT_6 pooled together reduced from 528 ms in block 11 to 455 ms in block 18. However, a repeated measures ANOVA with Visit (2; visit 1 & 2) as a within-subject factor showed that the RT decrease of key press 2 to 6 (pooled together) on visit 2 was less apparent compared to that of visit 1 (73 ms vs. 355 ms, respectively), $F(1, 17) = 23.500$, $p < .001$, $p\eta^2 = .580$.

<u>3-key sequence performance in the test phase</u>

A repeated measures ANOVA was conducted with Block Familiarity (2; familiar and unfamiliar test block) and Key (3; key 1 – 3) as within-subject factors. A main effect of Key indicated that there was a significant difference between the RTs of the 3 key presses in the test phase, $F(2, 34) = 11.304$, $p < .001$, $p\eta^2 = .399$. A main effect of Block showed that the mean RT of key press 1 to 3 pooled together was faster in the familiar test block than in the unfamiliar test block (mean RT in the familiar test block was 555 ms; mean RT in the unfamiliar test block was

790 ms), $F(1, 17) = 70.639$, $p < .001$, $p\eta^2 = .806$. A Block x Key interaction effect showed that the RT differences between the familiar and unfamiliar test block varied across the key presses of the 3-key sequence, $F(2, 34) = 27.860$, $p < .001$, $p\eta^2 = .621$.

A repeated measures ANOVA with Block Familiarity (2; familiar and unfamiliar test block) as a within-subject factor conducted on each key press showed a significant main effect of Block on RT_1, $F(1, 17) = 9.659$, $p = .006$, $p\eta^2 = .362$, which indicated that RT_1 was faster in the familiar test block than in the unfamiliar test block. This was also the case for RT_2, $F(1, 17) = 44.947$, $p < .001$, $p\eta^2 = .726$, and for RT_3, $F(1, 17) = 118.065$, $p < .001$, $p\eta^2 = .874$. As can be seen in figure 4, the mean difference of the mean of RT_2 and RT_3 pooled together between familiar and unfamiliar test block was larger than the difference of RT_1 between the two test blocks (307 ms vs. 91 ms, respectively).

When RTs of the 3-key sequence were examined in the familiar test block by conducting a repeated measures ANOVA with Key (3; key 1 – 3) as a within-subject factor, there was a main effect of Key that indicated that there was a significant difference between the RTs of the 3 key presses, $F(2, 34) = 21.402$, $p < .001$, $p\eta^2 = .557$. As can be seen in figure 4, RT_2 and RT_3 (489 ms and 465 ms, respectively) were faster than RT_1 (711 ms). A repeated measures ANOVA with Key (2; key 2 & 3) as a within-subject factor showed that there was no significant difference between RT_2 and RT_3 in the familiar test block, $F(1, 17) = 1.622$, $p = .220$, $p\eta^2 = .087$. When RTs of the 3-key sequence were examined in the unfamiliar test block by conducting a repeated measures ANOVA with Key (3; key 1 – 3) as a within-subject factor, it seemed that the RTs of the 3-key sequence did not vary significantly from each other in the unfamiliar test block, $F(2, 34) = 1.167$, $p = .324$, $p\eta^2 = .064$. The mean initiation-execution difference (IED) of the familiar 3-key sequence was 234 ms and 18 ms of the unfamiliar 3-key sequence. The mean difference between these two IEDs (i.e., 3-key chunking index) was 216 ms.

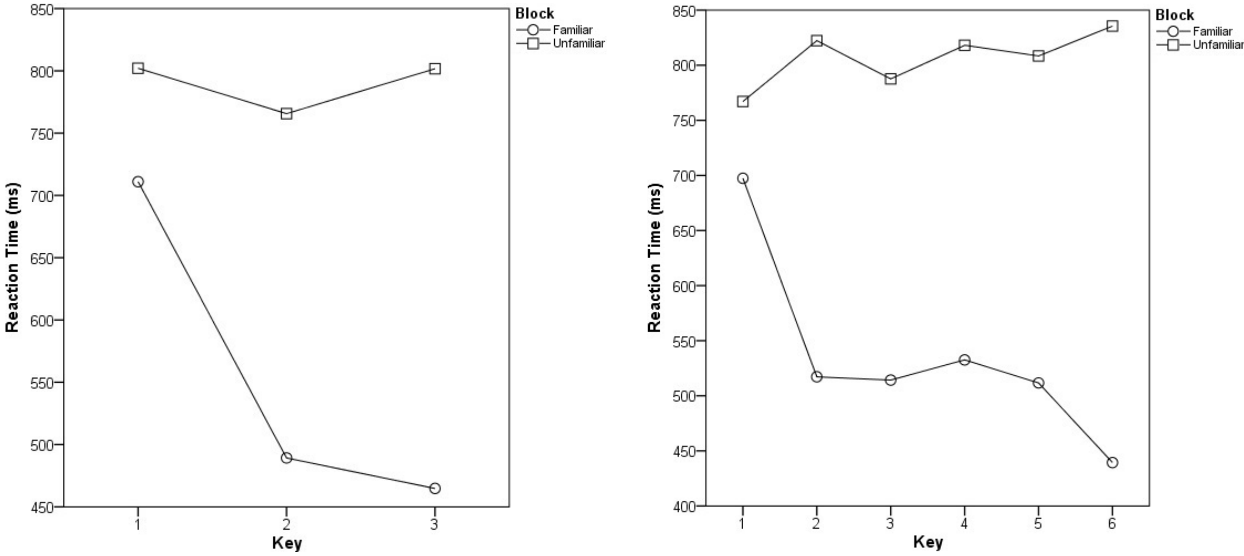


Figure 4. Mean RTs (in milliseconds) per key of the 3-key and 6-key sequence in each test block of visit 2 (familiar and unfamiliar test block).

<u>6-key sequence performance in the test phase</u>

A repeated measures ANOVA was conducted with Block Familiarity (2; familiar and unfamiliar test block) and Key (6; key 1 – 6) as within-subject factors. A main effect of Key indicated that there was a significant difference between the RTs of the 6 key presses in the test phase, $F(5, 85) = 3.455$, $p = .007$, $p\eta^2 = .169$. A main effect of Block showed that the mean RT of key press 1 to 6 pooled together was faster in the familiar test block than in the unfamiliar test block (mean RT in the familiar test block was 535 ms; mean RT in the unfamiliar test block was 807 ms), $F(1, 17) = 101.119$, $p < .001$, $p\eta^2 = .856$. A Block x Key interaction effect showed that the RT differences between the familiar and unfamiliar test block varied across the key presses of the 6-key sequence, $F(5, 85) = 10.430$, $p < .001$, $p\eta^2 = .380$.

A repeated measures ANOVA with Block Familiarity (2; familiar and unfamiliar test block) as a within-subject factor conducted on each key press showed a significant main effect of Block on RT_1, $F(1, 17) = 4.971$, $p = .040$, $p\eta^2 = .226$, which indicated that RT_1 was faster in the familiar test block than in the unfamiliar test block. This was also the case for RT_2 to RT_6, $Fs(1, 17) \geq 36.535$, $ps < .001$, $p\eta^2 \geq .682$. As can be seen in figure 4, the mean difference of the mean of RT_2 to RT_6 pooled together between familiar and unfamiliar test block was larger than the difference of RT_1 between the two test blocks (311 ms vs. 70 ms, respectively; a RT difference of 241 ms).

When RTs of the 6-key sequence were examined in the familiar test block by conducting a repeated measures ANOVA with Key (6; key 1 – 6) as a within-subject factor, there was a main effect of Key that indicated that there was a significant difference between the RTs of the 6 key presses, $F(5, 85) = 8.342$, $p < .001$, $p\eta^2 = .329$. As can be seen in figure 4, RT_2 (517 ms), RT_3 (514 ms), RT_4 (533 ms), RT_5 (512 ms) and RT_6 (439 ms) were faster than RT_1 (697 ms). A repeated measures ANOVA with Key (5; key 2 to 6) as a within-subject factor showed that there was no significant difference between the RTs (after sequence initiation) in the familiar test block, $F(4, 68) = 1.980$, $p = .107$, $p\eta^2 = .104$. When RTs of the 6-key sequence were examined in the unfamiliar test block by conducting a repeated measures ANOVA with Key (6; key 1 to 6) as a within-subject factor, it seemed that the RTs of the 6-key sequence did not vary significantly from each other in the unfamiliar test block, $F(5, 85) = 2.074$, $p = .077$, $p\eta^2 = .109$. The mean IED of the familiar 6-key sequence was 194 ms and -47 ms of the unfamiliar 6-key sequence. The mean difference between these two IEDs (i.e., 6-key chunking index) was 241 ms. Lastly, a repeated measures ANOVA with Sequence (2; 3-key & 6-key) as a within-subject factor showed that the 3-key chunking index and 6-key chunking index did not differ significantly from each other, $F(1, 17) = .297$, $p = .593$, $p\eta^2 = .017$ (214 ms vs. 223 ms, respectively).

The influence of DSP practice on visit 2 on motor chunking

In order to determine whether the DSP practice on visit 2 had influence on further chunking of the 3-key and 6-key sequence, the chunking in block 18 (i.e., at the end of the practice phase on visit 2) was compared to that in block 9 (i.e., at the end of the practice phase on visit 1). Thus, the IEDs of the 3-key and 6-key sequence in block 9 were compared to those of block 18. A repeated measures ANOVA with Block (2; practice blocks 9 & 18) as a within-subject factor was conducted on the 3-key IEDs and 6-key IEDs. It appeared that the 3-key IED did not vary significantly across the two blocks, $F(1, 17) = .062$, $p = .806$, $p\eta^2 = .004$ (mean IED was 227 ms in block 9 and 216 ms in block 18). The 6-key IED also did not vary significantly across block 9 and 18, $F(1, 17) = 3.125$, $p = .095$, $p\eta^2 = .155$ (mean IED was 171 ms in block 9 and 211 ms in block 18). In other words, the 3-key and 6-key IED was not significantly larger in block 18 compared to block 9, meaning that there was no significantly more chunking at the end of the practice phase of visit 2 than at the end of visit 1.

In figure 5, it can be seen that chunking (indicated as IED) generally increased across the blocks of visit 1 for both the 3-key and the 6-key sequence. However, the IED decreased at the beginning of visit 2 compared to that at the end of visit 1. Moreover, the IED seemed to increase across the practice blocks of visit 2 as well but compared to the IED in block 9, the IED was not significantly more apparent in block 18 for both sequences, according to the above ANOVAs.

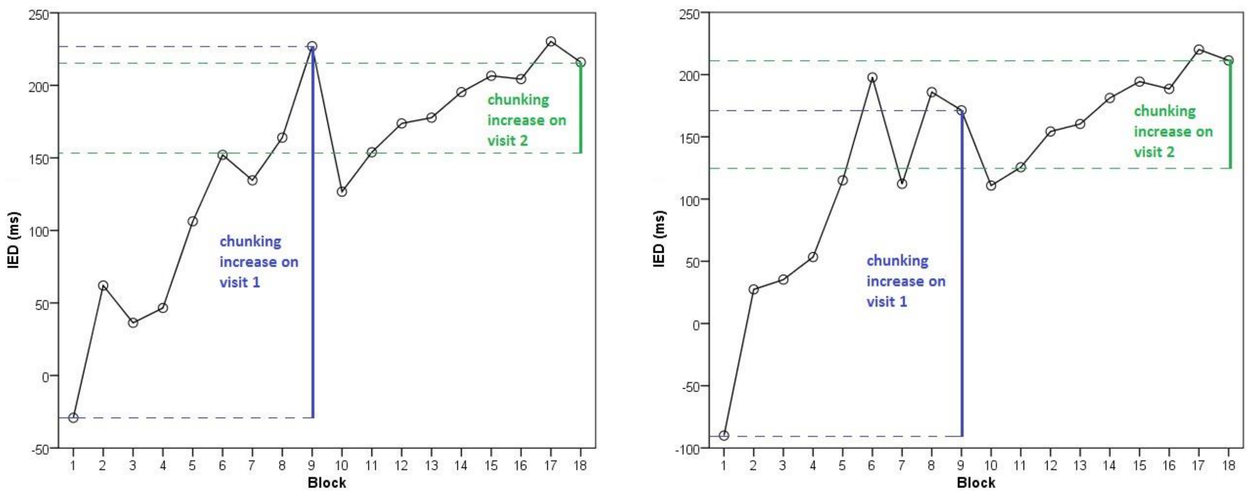


Figure 5. Chunking (indicated as IED) of the 3-key sequence per block (left graph) and chunking of the 6-key sequence per block (right graph): it was calculated by subtracting the mean RT of the sequence execution (3-key: mean of RT_2 and RT_3; 6-key: mean of RT_2, RT_3, RT_4, RT_5 and RT_6) from RT_1 (sequence initiation) of that particular block.

<u>Concatenation on visit 1 and visit 2</u>

As can be seen in figure 6, participants showed chunking in block 9 and 18. However, the graph of block 9 showed an increased RT of key press 4 and 5 compared to the RTs of key press 2, 3 and 6. This increased RT could not be found in the graph of block 18. The higher RTs after sequence initiation in block 9 might be the concatenation points of the 6-key sequence, when looking at the data of the participants as a group. As the position of the concatenation point could vary from participant to participant, the individual concatenation point of each participant was determined in block 9 which was the highest RT after initiation for that particular participant. RT_2 was the highest RT after initiation for 3 participants. This was RT_3 for 3 other participants, RT_4 for 7 participants, RT_5 for 4 participants, and RT_6 for 1 participant. The difference between the *concatenation point* and *the mean of the 4 other key presses* (RT_1 and RT of concatenation point excluded) in block 9 was calculated. The same key press (i.e., the concatenation point in block 9) was used in block 18 and the difference between the *concatenation point* and *the mean of the 4 other key presses* in block 18 was calculated. To see if the above-mentioned RT difference varied across block 9 and 18, a repeated measures ANOVA was conducted with Block (2; block 9 & 18) as a within-subject factor. Results showed that the RT difference was significantly smaller in block 18 compared to block 9 (104 ms and 193 ms, respectively), $F(1, 17) = 6.066$, $p = .025$, $p\eta^2 = .263$, suggesting that the concatenation point was not so apparent in block 18 compared to that in block 9.

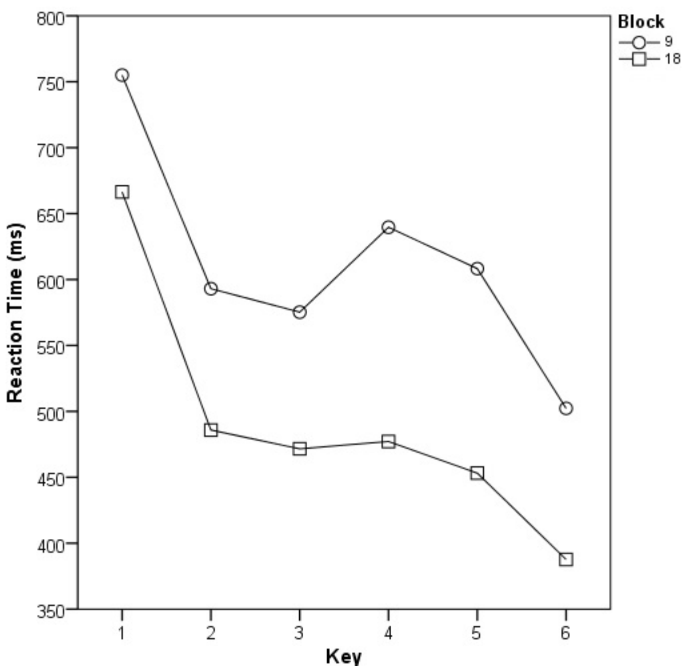


Figure 6. Mean RTs (in milliseconds) per key of the 6-key sequence in the last practice block of visit 1 and 2.

<u>DSP performance at the end of visit 1 vs. DSP performance at the beginning of visit 2</u>

Regarding the RTs of the 3-key sequence at the end of visit 1 (i.e., block 9) and at the beginning of visit 2 (i.e., block 11), a repeated measures ANOVA with Block (2; practice blocks 9 & 11) as a within-subject factor showed that the initiation-execution difference in block 9 (mean IED: 227 ms) was not significantly different from that in block 11 (mean IED: 154 ms), $F(1, 17) = 2.973$, $p = .103$, $p\eta^2 = .149$. Regarding the RTs of the 6-key sequence at the end of visit 1 (i.e., block 9) and at the beginning of visit 2 (i.e., block 11), the initiation-execution difference in block 9 (mean IED: 171 ms) was also not significantly different from that in block 11 (mean IED: 126 ms), $F(1, 17) = 2.421$, $p = .138$, $p\eta^2 = .125$. These results indicate that the chunking behavior at the beginning of visit 2 did not vary significantly from that at the end of visit 1. It was not necessary for them to develop motor chunks all over again. Participants showed motor chunking early on visit 2, due to DSP task practice on visit 1.

Correlations

To assess the relationship between the VAC score or the digit-symbol substitution score and a chunking index (i.e., general chunking index, 6-key chunking index or 3-key chunking index), a Pearson product-moment correlation coefficient (Pearson's r) was calculated.

Results showed that the VAC score was not significantly correlated to the general chunking index, $r(n = 18) = -.028$, $p = .911$, to the 6-key chunking index, $r(n = 18) = -.108$, $p = .671$, or to the 3-key chunking index, $r(n = 18) = .089$, $p = .725$. Furthermore, digit-symbol substitution score was also not significantly correlated to the general chunking index, $r(n = 18) = -.386$, $p = .113$, to the 6-key chunking index, $r(n = 18) = -.452$, $p = .060$, or to the 3-key chunking index, $r(n = 18) = -.139$, $p = .582$. In other words, the visuospatial working-memory capacity and the speed of information processing could not predict the size of the 3-key, 6-key or general chunking index.

With regards to whether the chunking indices correlated to each other, results showed that there was no significant correlation between the 6-key chunking index and the 3-key chunking index, $r(n = 18) = .338$, $p = .170$ (see figure 7). On the basis of the scatterplot in figure 7, participants could generally be divided into two groups: 9 participants showed a larger chunking index for the 3-key sequence than for the 6-key sequence (mean difference was 130) and the other half of the participants showed a larger chunking index for the 6-key sequence than for the 3-key sequence (mean difference was 182). As it was possible that the presence of the two different groups might be responsible for the reduction of the significance of the correlation, in each group the correlation between the chunking indices was also computed. Figure 8 showed that the data points of one group seem to be generally different from the other group, in that the data points from one group clearly deviate from the original regression line of the data points in the other group. Thus, this could decrease the size of the correlation coefficient and the significance of the correlation when all data points were included in the computation of the correlation (also see figure 7). Results showed that there was a significant positive correlation between the 3-key and the 6-key chunking index in the group that showed a higher 3-key chunking index, $r(n = 9) = .780$, $p = .013$, and in the group that showed a higher 6-key chunking index, $r(n = 9) = .704$, $p = .034$ (see figure 8). In short, no clear association between the 3-key and 6-key chunking index could be found when all data points (from both groups) were used in the calculation of the correlation. The data points of the scatterplot were scattered in such a way that they did not approximate a clear straight line. However, when data points were examined in each group, strong positive correlation could be found between the two chunking indices.

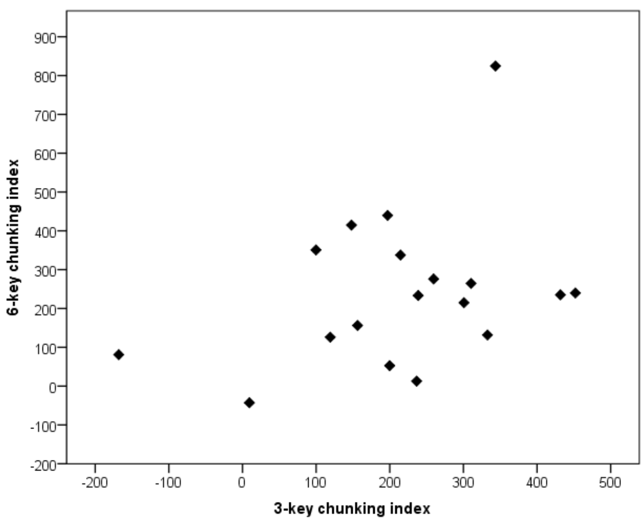


Figure 7. Scatterplot of the 6-key chunking index and the 3-key chunking index.

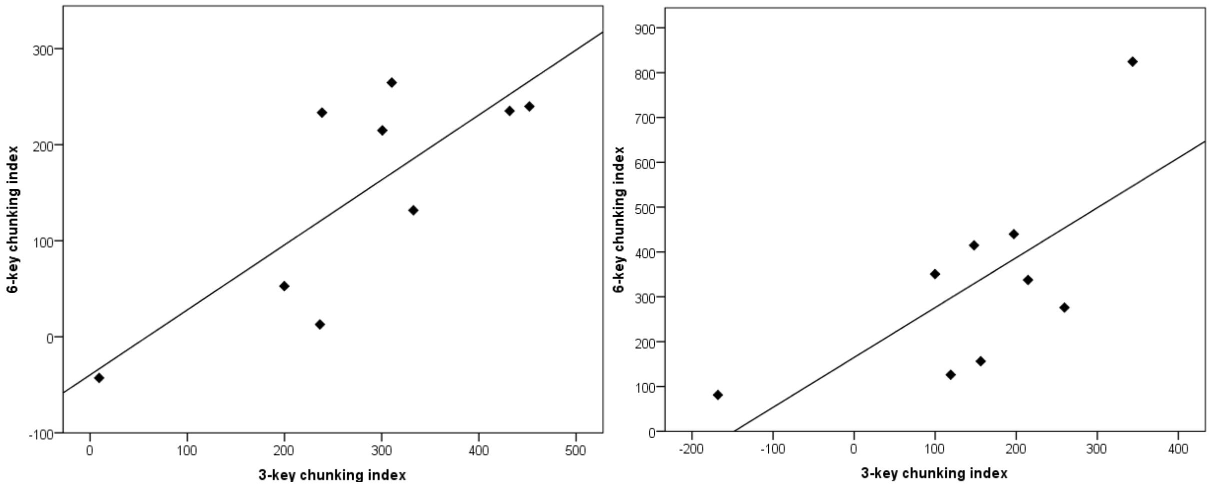


Figure 8. Left scatterplot: scatterplot of the 3-key chunking index and the 6-key chunking index of only the participants who had a higher 3-key chunking index compared to their 6-key chunking index. Right scatterplot: scatterplot of the 3-key chunking index and the 6-key chunking index of only the participants who had a higher 6-key chunking index compared to their 3-key chunking index.

Chunking indices

According to figure 9, it seemed that about half of the older participants of the study of Verwey (2010) showed a negative chunking index, which indicated that these participants did not use motor chunks to perform the 3-key and 6-key sequences. This was in contrast with the DSP performance of the older participants of this study. Nearly all participants showed a positive chunking index and thus used motor chunks to execute the sequences. Chunking indices of this study suggested that the degree of motor chunking is similar to that of the young adults in the study of Verwey (2010).

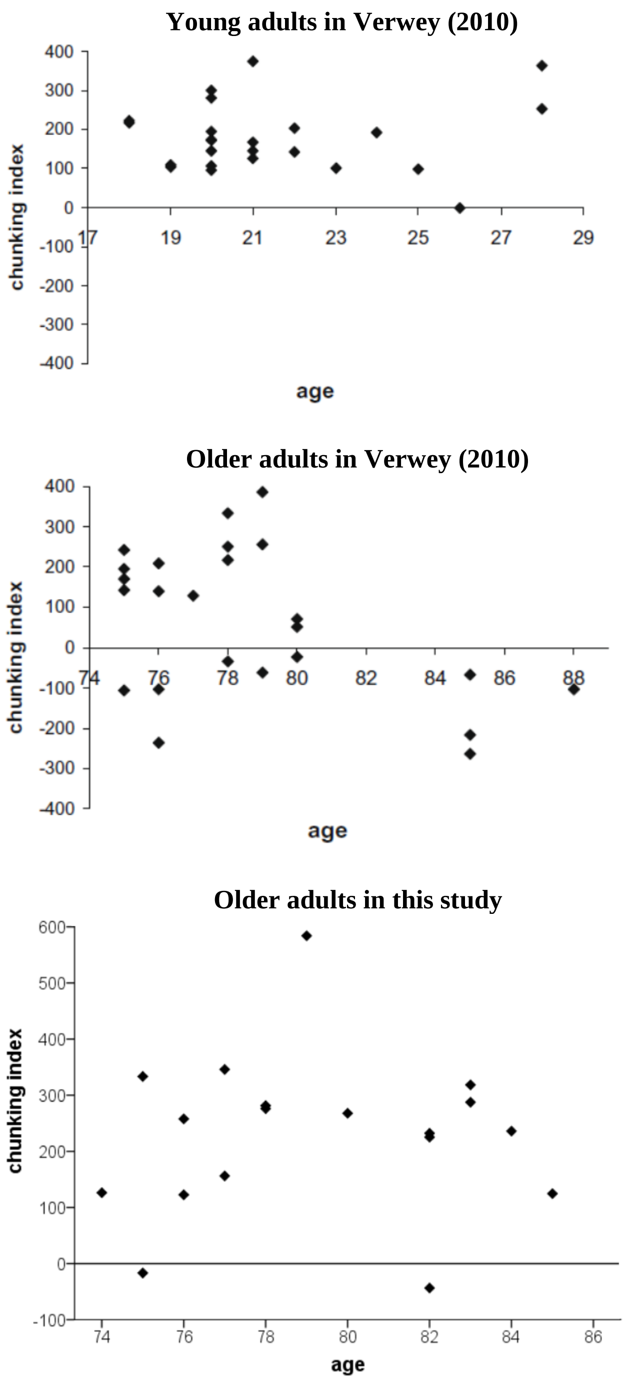


Figure 9. The top two scatterplots indicate the general chunking index and age of the participants in the study of Verwey (2010). The bottom scatterplot indicates the general chunking index and age of the participants in this study.

Discussion

This study investigated whether older adults showed motor chunking when performing the motor sequences after extended practice. Results showed that chunking indeed took place: the key presses after sequence initiation were faster than RT_1. It was expected that the older participants would show chunking after extended practice on visit 2. However, results indicated that participants already displayed chunking after practice on visit 1 for both sequences. Furthermore, there seemed to be more chunking at the end of visit 2 compared to the chunking at the end of visit 1 for the 6-key sequence (as can be seen in figure 5). This increase in chunking was not found for the 3-key sequence. It was possible that the older adults already reached their optimum performance of the 3-key sequence on visit 1. However, visit 2 was still needed to improve their performance of the 6-key sequence, which could be attributed to the fact that the 6-key sequence was a more difficult motor sequence to learn compared to the 3-key sequence.

The general chunking indices of this study showed that the degree of motor chunking is similar to that of the young adults and in contrast to that of the older adults in the study of Verwey (2010). This difference in DSP performance could be attributed to the amount of practice trials for each sequence that varied between the study of Verwey (2010) and this study (144 trials vs. 432 trials, respectively). However, figure 1 and figure 3 show that there was already a clear difference between the RT of sequence initiation and the RTs of the subsequent key presses in practice block 6 for both sequences. Performance of block 6 is mentioned here to compare it with the performance of the practice phase of Verwey (2010) which had 6 practice blocks in total. It seemed that participants already used motor chunks in block 6 in this study, which was in contrast with the sequence performance of the older adults in the study of Verwey (2010) as no clear indications of chunking were observed when RTs were examined at the group level. Moreover, the conditions in which the participants were tested varied between the studies. In the study of Verwey (2010), participants were tested at their home, whereas the participants in this study were invited to do the experiment in the lab of the university. It is a possibility that more able older adults participated in this study. Moreover, the apparatus for the DSP task was different in the two studies. In the study of Verwey (2010), a 10.6” notebook was used (with 16 x 16 mm keyboard keys) whereas a regular personal computer with a 22” monitor (with 19 x 19 mm keys) was used in this study.

Another interesting finding was that the concatenation point of the 6-key sequence became less apparent (i.e., an indication of more chunking) after extended practice. Several motor chunks might be used when performing the 6-key sequence (first motor chunk: RT_1 to concatenation point & second motor chunk: concatenation point to RT_6). According to Verwey, Abrahamse and de Kleine (2010), the concatenation phase might be involved in the loading and initiation of the subsequent motor chunk. After extended practice, the loading of the upcoming motor chunk could become faster. It is a possibility that with further practice, the concatenation point could even become less noticeable to the point that the 2 motor chunks of the 6-key sequence might start to become one large motor chunk. This might indicate that the 6-key sequence performance becomes even more automatic. It might be interesting to see what would happen if this study is to be repeated with younger adults to observe whether the concatenation point would be even less apparent after extended practice (compared to that of the older adults) which might be an indication of more efficient concatenation between motor chunks.

Limitations

Regarding the chunking per block, it was noticeable that chunking in block 7 seemed to decrease compared to block 6, especially for the 6-key sequence. This might have to do with the fact that after block 6, the participants did not immediately continue with block 7 but had to do the digit-symbol substitution test first which might have slightly distracted the participants from the DSP task. A point of improvement might be to give the digit-symbol substitution test at the beginning or at the end of visit 1.

All 18 participants indicated that the VAC task was too difficult to perform. Specifically, the sample array of colored squares was presented too shortly (100 ms) in their opinion, often leading them to take a random guess when determining whether the sample array was the same as the test array or not. This might be the reason why no correlations were found between the VAC score and the chunking indices. A point of improvement might be to display the sample array a little longer (e.g., 200 ms). This could decrease the amount of random guessing and might assess the visuospatial working-memory capacity more accurately. This way, more accurate and significant correlations between the VAC score and the chunking indices could then be found.

Correlation between the 3-key and 6-key chunking index

It was surprising to see that there was no correlation between the 6-key chunking index and the 3-key chunking index, as it was expected that chunking is an ability that could be demonstrated to a greater or lesser extent. Without correlation between the chunking indices, it suggested that participants could not be considered good or bad in chunking of the sequences. For example, a participant could show high chunking when performing a 3-key sequence but low chunking with a 6-key sequence (and vice versa).

In relation with the effect of working memory capacity on chunking, the question could be posed whether the hypothesis that working memory processes (e.g., visuospatial working-memory or speed of information processing) could predict whether someone is good or bad in chunking, is sensible since a lack of correlation between the chunking indices suggests that chunking may not be an ability that systematically varies between participants in the first place. As can be seen in figure 8, the reason of the lack of correlation was because the data points of the scatterplot of the participants who showed a higher 6-key chunking index compared to their 3-key chunking index (i.e., group 1) generally fell some distance away from the regression line of the group that showed a higher 3-key chunking index compared to their 6-key chunking index (i.e., group 2). However, when the scatterplot data points were examined in each group separately, strong positive correlations were found between the 3-key and the 6-key chunking index.

It was interesting to see that half of the participants displayed a higher 3-key chunking index, whereas the other half showed a higher 6-key chunking index. The performance of group 2 might be due to an earlier awareness of the fixed pattern of the 3-key sequence as this sequence was easier to learn for them. These participants reached the chunking mode earlier when performing the 3-key sequence than when they performed the 6-key sequence. This way, there was more opportunity to perform the 3-key sequence as a chunk which in turn caused a larger initiation-execution difference in the 3-key sequence compared to that in the 6-key sequence (hence the higher 3-key chunking index). However, further examination is needed to understand why group 1 showed more chunking when performing a 6-key sequence, compared to their 3-key sequence performance.

Implications

How can the result of older participants showing motor chunking after sufficient DSP practice and the result of diminished concatenation point after extended DSP practice be interpreted when looking at real-life motor behaviors? To illustrate this, an example is given of a new motor behavior that older adults may want to learn. For example, some older adults may want to learn to play golf after their retirement. The basic movement of playing golf is the golf swing which is comprised of various submovements that are important to properly execute the entire swing: the address position, the backswing, the downswing and the follow through. In order to correctly perform the perfect golf swing, the submovements have to be mastered first. Each submovement consist of smaller movements that also have to be mastered. For example, the address position requires the golfer to open the feet to shoulder width, to lock the knees, to tilt the upper body to the right so that the head is behind the ball, to bend from the hips, to keep the shoulder blades back and the spine straight, and to set the golf club behind the ball. To make a reference to the results of this study, these above-mentioned smaller movements are analogous to the key presses of a motor chunk (e.g., the first motor chunk of the 6-key sequence). With practice, it will be easier to perform all the smaller movements to the point that the action of getting in the correct address position becomes an integrated motor pattern which is similar to the key presses that are combined into a motor chunk. Regarding the mastering of the other golf swing submovements, an integrated motor pattern will also develop for each submovement after sufficient training. If all submovements improve sufficiently, the golfer can begin to incorporate all submovements into the entire golf swing movement. In the beginning, this person may still have to think of the individual actions of each submovement and the correct order of the submovements. With further practice, these submovements will become part of an even bigger integrated movement pattern in which the submovements will be carried out automatically one after another. This is analogous to the motor chunks of the 6-key sequence that became more concatenated after extended practice on visit 2.

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Appendix

List of the performed sequences

Participant #	Familiar 6-key	Familiar 3-key
1	KFGDJL	FKL
2	LGJFKD	GLD
3	DJKGLF	JDF
4	FKLJDG	KFG
5	GLDKFJ	LGJ
6	JDFLGK	DJK
7	KFGDJL	FKL
8	LGJFKD	GLD
9	DJKGLF	JDF
10	FKLJDG	KFG
11	GLDKFJ	LGJ
12	JDFLGK	DJK
13	KFGDJL	FKL
14	LGJFKD	GLD
15	DJKGLF	JDF
16	FKLJDG	KFG
17	GLDKFJ	LGJ
18	JDFLGK	DJK

Note. There are six different 6-key and six different 3-key sequences.