# THE INFLUENCE OF VERBAL SEQUENCE KNOWLEDGE ON MOTOR CHUNK LEARNING

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**Bachelor thesis**

June 2015

University of Twente

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## Abstract

The aim of the study was to examine whether the usage of both working memory structures, the visuospatial sketchpad and the phonological loop, instead of only one can enhance task performance in sequence learning. Therefore, the current study investigated whether pre-experimental verbal sequence learning supports task performance in a discrete sequence production (DSP) task with two phases. In this research, 24 participants (students of the University of Twente) were split into two groups of which the experimental group verbally learned two sequences relevant for the practice phase whereas the control group verbally learned two sequences relevant for the test phase. The practice phase included four identical blocks, while the test block consisted of one block containing three different test conditions: a learned sequence condition, a partially learned sequence condition and a new sequence condition. The analysis of the practice phase revealed lower reaction times for the experimental group on Key 1 in Block 1, meaning that these participants needed less time to react to the stimuli than the participants of the control group. However, this effect vanished over the course of the other blocks. The analysis of the test phase revealed that the performance of both groups differed from condition to condition while there was no difference in performance between them. Verbal sequence knowledge thus benefits the generation of motor chunks and supports motor sequence learning in the first phase of learning. Additionally, motor chunks also benefit sequence performance when sequences only consist of parts of the learned sequences.

## Samenvatting

Het doel van dit onderzoek was te kijken of het gebruiken van twee werkgeheugen componenten, het visuo-spatieel kladblok (‘visuospatial sketchpad’) en de fonologische lus (‘phonological loop’), in plaats van één de prestatie bij het leren van twee series van letters kan verhogen. Deze studie heeft onderzocht of het verbaal leren van twee letter series voorafgaand aan het experiment helpt om de prestatie op een discrete sequence production (DSP) task met twee fasen te verhogen. In dit onderzoek werden 24 proefpersonen (studenten van de Universiteit Twente) over twee groepen verdeeld: de experimentele groep leerde twee sequenties verbaal, die relevant waren voor de oefenfase, voorafgaand aan het onderzoek. De controle groep daartegen leerde twee sequenties verbaal, die belangrijk waren voor de testfase van het onderzoek. De oefenfase van het experiment bestond uit vier gelijk opgebouwde blokken, hoewel de testfase uit maar één blok met drie verschillende condities bestond, die alle proefpersonen moesten doorlopen: een geleerde sequentie conditie, een gedeeltelijk geleerde sequentie conditie en een nieuwe sequentie conditie. De analyse van de oefenfase liet zien dat er kortere reactie tijden voor de experimentele groep op Key 1 in Blok 1 waren: de proefpersonen uit deze groep hadden minder tijd nodig om op de stimuli te reageren dan proefpersonen uit de controle groep. Desondanks verdween het effect ten opzichte van de andere drie blokken. De analyse van de testfase toonde aan dat de prestatie van beide groepen verschilde met betrekking tot de drie condities, maar er was geen significant verschil in de prestatie van de twee groepen ten opzichte van elkaar. Verbale kennis van sequenties helpt dus om motor chunks op te bouwen en is nuttig bij het leren van motor sequenties in het begin. Bovendien steunen motor chunks de prestatie zelfs als de sequenties maar uit stukjes van de geleerde sequenties bestaan.

## Introduction

Nearly all goals we set during our daily life consist of series of movements, such as cooking our favourite meal or playing a piece of music on an instrument. Although, with experience, all of these activities can be accomplished without great involvement of attention, these series of movements have been consciously learned at some point in our life. For example, before being able to play a piece of music on an instrument fluently, most learners need to attend to every note carefully one by one. With ongoing practice, the abilities of the learner grow and he or she will be able to reduce cognitive capacities while playing single bars and being able to concentrate on the next. Then, if practice is still continued, the learner will achieve greater autonomy and will be able to play the piece of music fluently in the end. Practice thus leads to the development of an automatism, which enables the learner to focus on other task-relevant details, such as the intensity of sounds and correct manners of breathing (e.g. in flutists or trumpeters).

In order to be able to accomplish a particular task automatically, the learner has to engage in a process of learning: Herein, the learner first has to attend each stimulus individually to be able to choose the correct corresponding response movement before processing the next stimulus (Bo, Jennett & Seidler, 2011). Then, with practice, associations are built between the stimuli and the corresponding responses (Verwey, Abrahamse & Jiménez, 2009). With more extensive practice, these individual associations will be connected to each other until the learner is able to execute the movement by responding only to the first stimulus being presented (Verwey, Abrahamse & Jiménez, 2009; Abrahamse, Ruitenberg, de Kleine & Verwey, 2013; Ruitenberg, Verwey, Schutter & Abrahamse, 2014). The connection of responses according to their “temporal proximity” as well as with regard to their content is called chunking (Abrahamse et al., 2013, p. 6). A chunk is thus assumed to be a memory representation for a limited number of (motor) responses bearing references to each other (Verwey & Eikelboom, 2003; Verwey, Abrahamse & Jiménez, 2009; Bo, Jennett & Seidler, 2011; Abrahamse et al., 2013). As practice is continued, the chunk will in turn elicit the learned responses, retrieved from long-term memory (Bo, Jennett & Seidler, 2011).

The model explaining the generation process of motor chunks is the dual processor model (DPM) (Verwey, 2001). According to Verwey, Abrahamse, De Kleine and Ruitenberg (2014), the dual processor model claims that two distinct processors are responsible for sequence learning: a cognitive processor, which is thought to be responsible for preparing and selecting the movement, and a motor processor, which is assumed to be responsible for the execution of the movement. During the earliest stage of learning, the reaction mode, the cognitive processor is responsible for enabling a person to accomplish the task by means of translating single stimuli into responses (Abrahamse et al., 2013; Ruitenberg et al., 2014). Verwey (2001) assumes that the slow execution speed of sequence movements occurring here is due to the cognitive processor's characteristic to translate each stimulus into a response one by one. After translation, the cognitive processor loads a motor buffer, which is in turn read by the motor processor: the second processor underlying the dual processor model (Abrahamse et al., 2013). With ongoing practice, the learner is assumed to be in the associative mode (Ruitenberg et al., 2014). Herein, performance is not yet supported by the usage of motor chunks, but the learner still benefits from practice due to the generation of associations between stimuli and responses (Verwey, Abrahamse & Jiménez, 2009; Abrahamse et al., 2013; Ruitenberg et al., 2014). As practice is continued, motor chunks are generated: The motor buffer is not only loaded with single responses coming from the cognitive processor, but may also receive multiple responses in the form of motor chunks (Verwey, 2001). With even more extensive practice, the cognitive processor will eventually load the motor buffer with only a single motor chunk from memory (Bo, Jennett & Seidler, 2011; Abrahamse et al., 2013; Ruitenberg et al., 2014). In this so-called chunking mode, the motor processor is to execute the series of movements very much autonomously from the cognitive processor. Sequence production is thus characterized by little cognitive processor involvement, since it only needs to trigger the motor processor to read the code from the motor buffer in only one single step (Ruitenberg et al., 2014).

One way to study the development of motor chunks is the discrete sequence production (DSP) task of Verwey (2001). At the beginning of the DSP task, the participants place four to eight fingers on a computer keyboard, depending on the number of stimuli that the sequence will contain. On the computer screen, the same number of placeholders is shown, which mostly consist of squares in a row (Abrahamse et al., 2013). According to Abrahamse et al. (2013), the task begins when one of the placeholders lights up. Then, "the participant is instructed to rapidly press the spatially corresponding key" (Abrahamse et al., 2013, p. 2). Only if the correct key has been pressed, the next stimulus will be displayed on the screen. The DSP task mostly consists of two sequences, which are usually repeated 500 to 1000 times each. These are executed in a random order and usually contain three to seven stimuli. The DSP task begins with a practice phase in which participants are expected to develop motor chunks required for the development of an automatism (Abrahamse et al., 2013). Automatisms are series of movements characterized by rapidity, accuracy and relatively little amounts of attentional and cognitive involvement of the person (Tracy, Pinsk, Helverson, Urban, Dietz & Smith, 2001; Gasbarri, Pompili, Packard & Tomaz, 2014). According to Shiffrin and Dumais (1981) as well as Gupta, Vig and Noelle (2012), the series of movements can be accomplished very much autonomously, which in turn frees mental resources for the performance of secondary tasks.

Since the learned automatisms containing series of movements are eventually stored in long-term memory, the involvement of working memory is of particular interest at this point in learning as well. Seidler, Bo and Anguera (2012) have argued that the structures involved in early learning of sequences are dependent on particular working memory structures, which have been described in the working memory model of Baddeley and Hitch (1974). According to Baddeley and Hitch (1974), this model states that working memory consists of three distinct components for storing information: a central executive, a visuospatial sketchpad and a phonological loop. The central executive is responsible for controlling the other two instances. Smith and Kosselyn (2009) as well as Berk (2009) suggest that the central executive is activated when information of any kind is presented: it determines which of the two memory storage buffers shall be activated to store and maintain the information, the phonological loop, the visuospatial sketchpad or both. However, the central executive is not able to store information itself (Baddeley, 2003). Therefore, a fourth component has been added to the model. It is also responsible for the coordination as well as the integration and combination of information from these two instances (Baddeley, 2003).

The visuospatial sketchpad in turn can be understood as a subsystem responsible for the integration of visual and spatial information into working memory (Baddeley, 2003; Wickens, 2004; Smith & Kosselyn, 2009). According to Smith and Kosselyn (2009), the visuospatial sketchpad functions like a “mind’s eye” (Smith & Kosselyn, 2009, p. 257) for the storage of locations and places in space. The visuospatial sketchpad is analogous to the phonological loop, which is a structure responsible for verbal and acoustic information (Baddeley, 2003; Wickens, 2004). According to Baddeley (2003), in learning a sequence of letters for immediate use, learning will depend to great amounts on the acoustic and phonological properties of the sequence: when, for example, trying to memorize a password consisting of a combination of random letters, the information and order of the letters is held in the phonological loop, once the information has been verbalized. Smith and Kosselyn (2009) describe this as if the “information is spoken internally by the mind’s voice in rehearsal” which can in turn be “heard by the mind’s ear and maintained in the phonological loop” (Smith & Kosselyn (2009), p. 251).

The literature consulted for this experiment contained studies dealing exclusively with visually presented information in the DSP task. With reference to the working memory model of Baddeley and Hitch (1974), these studies are assumed to only have assessed the involvement of the visuospatial sketchpad in the development of sequence knowledge: Seidler, Bo and Anguera (2012), for example, found that visuospatial working memory capacity correlates positively with the chunking pattern of the learned sequence with respect to chunk length, as well as with the execution rate of early motor sequence learning. Since Seidler, Bo and Anguera (2012) have solely taken the memory storage involvement of the visuospatial sketchpad into account, the current research is aimed at investigating possible benefits of using both verbal and spatial memory storages in sequence learning. Therefore, this study explores whether pre-experimental verbal learning of two particular sequences will support sequence learning during a classical DSP task. At the same time, the current study examines whether this pre-experimental verbal learning also benefits sequence learning when the sequences of the task consist only of pieces of the previously practiced sequences.

To measure the extent to which sequence learning is supported by pre-experimental verbal learning, participants were distributed over two groups: a control and an experimental group. The basic procedure of the experiment was similar for both groups. The only difference between them was that the control group learned two sequences that were not used in the practice phase of the DSP task. Instead, they received two unknown sequences to be learned during this phase. Their pre-experimental verbally learned sequences resembled those two sequences that needed to be performed in the test phase in one of the three conditions: the partially learned sequence condition.

According to the literature, it was expected that participants of the experimental group would have an advantage in performance rate over those of the control group with respect to the practice phase. This was due to the support of their previously generated verbal chunks on the building of motor chunks and memory representations for the two sequences. However, this effect was predicted to vanish over the course of the blocks because all participants will be able to generate motor chunks due to extensive practice.

For the test phase, it was assumed that participants of the control group would outperform those of the experimental group especially in the partially learned sequence condition. This was anticipated because participants of the control group are able to build sequence knowledge both verbally and spatially: Prior to the experiment, they build verbal chunks on the sequences due to verbal rehearsal. Additionally, they developed motor chunks on parts of the sequences during the practice phase of the DSP task similarly to the participants of the experimental group. Therefore, it is expected that participants of the control group will perform the partially learned sequence condition quicker than participants of the experimental group.

# Method

## Participants

24 students (11 male and 13 female) of the University of Twente participated in this study. Their mean age was 21.4 years, S.D. = 1.9 years, and they gained three course credits for their participation.

## Material

The experiment was accomplished on a Windows 7 computer, which was started in a modus where unnecessary services were turned off (e.g. Windows automated update search, etc.). A flat screen with the size of approximately 17 Inch was used, as well as a Sennheiser PC3 headset for the audio recording. The software utilized in this study was E-Prime 2.0.

## Tasks

### *Audio Recording*

The computer screen displayed a 1x1cm² black fixation cross in the middle of a white background screen. This cross was placed there to mark the beginning of the audio recording. Following the removal of the cross, the computer chose one letter from a selection of four letters made by the experimenter from the initial six letters D, F, G, J, K or an L. The selection always included the two initial letters of the two sequences as well as two randomly chosen letters. The letters were always displayed one by one. Participants were supposed to respond to this letter with either the word "pas" (if the letter was not marking the beginning of one of the learned sequences) or with naming the six-letter sequence that began with this letter. After each displayed letter, there was a four second period to give the participants time to answer. The responses were recorded with a microphone. Each learned sequence was to be reproduced three times. In total, the task contained twelve trials. After the recording, the experimenter monitored the sequences on fluency and correctness to ensure the participants knew the sequences. In the case, the participant made mistakes during the audio recording, they got ten minutes to properly learn the sequences, and the task was repeated until the recording contained no mistake. This data will not be reported in this thesis.

*DSP Task*

In the DSP task, participants were instructed to place the left hand's ring, middle and index finger on the keys "D", "F" and "G" on the computer keyboard as well as the right hand's index, middle and ring finger on the "J", "K" and "L", respectively (see Fig. 1). In the middle of the screen, six squares were displayed containing the letters corresponding to the sequences and the fingers on the keyboard. The six squares were split into groups of three including a space left for the "H" key on the keyboard (which was not displayed on the screen, but left blank). The two sequences to be reacted to were displayed below the six squares as a row of six letters one at a time. As soon as the first correct key of the keyboard was pressed, this row disappeared and six dashes were displayed. If a wrong key had been pressed or a key had been pressed too early, an error message appeared and was followed by the next sequence. The whole DSP task consisted of four practice blocks and one test block (Appendix I). The former contained 360 sequence repetitions each. Thus, every sequence was displayed 180 times per block. In total, each sequence was practiced 720 times per participant.

The test block consisted of three test conditions, each incorporating 40 trials, which were counterbalanced across the participants. One condition consisted of the sequences that participants had learned during the practice phase with 20 trials per sequence. Another consisted of sequences, which were made up of pieces of the learned sequences of the practice blocks: each of the two learned sequences was split up into parts of three letters (e.g. "FKLJDG" and "KFGDJL" were split into "FKL-JDG" and "KFG-DJL"). Then, these pieces were matched with the corresponding part of the other sequence: the second part of the first sequence was matched with the first part of the second sequence and vice versa (e.g. "JDG-KFG" and "DJL-FKL", see Appendix I). For the control group, these sequences resembled the whole two sequences that were verbally learned prior to the experiment. This test condition is of particular importance for testing whether pre-experimental verbal learning still helps to enhance task performance after several practice trials of another sequence. For the experimental group, the sequence arrangement was new, because the learned sequences were split. A third condition of the test phase consisted of two sequences made up of two totally new arrangements of the six letters.

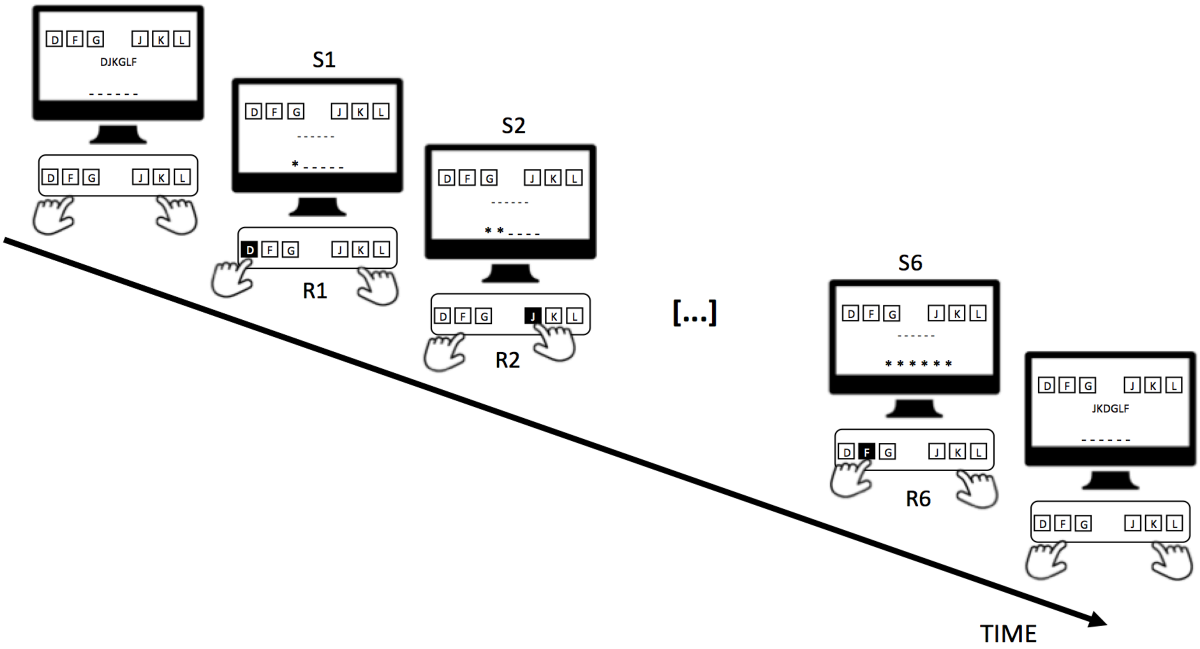


*Figure 1*: **Description of the DSP task utilized in this study. Participants responded (R1-R6) to six stimuli (S1-S6).**

*Awareness test*

Six squares (black outline) were displayed on the white background of the computer screen. They were arranged in either of two manners: in a row or in a circle. The two manners of arrangement were used to test either spatial or verbal representation in the participants, respectively. The squares in a row contained no letters, but were arranged in the same way as the particular keys on the keyboard. The squares arranged in a circle contained all six letters. Participants were asked to use the computer mouse to click on the squares in the order of both sequences without looking on the keyboard. After both tasks, participants were asked to answer two questions on the sequences and their reproduction. These questions were also displayed on the computer screen: 'Did you look on the keyboard?' and 'How sure are you about the order of the letters, you just clicked on?'.

**Procedure**

In advance of the study, participants received the two particular sequences to be learned via e-mail asking them to learn these until they could recite them freely and without mistakes. At the beginning of the study, participants filled out a form asking them of their name, the date and the time. Hereafter, they were given an instruction to the procedure of the study, which explained the different tasks and their order. Additionally, they read and signed an informed consent form.

The study began with the audio recording of the sequences, participants had to learn. Hereafter, the experimenter monitored the sequences on correctness and fluency to ensure the participant's performance in the further study. In the case, the participant made mistakes during the audio recording, they got ten minutes to properly learn the sequences, and the task was repeated until the recording contained no mistake.

Hereafter, the participants received the first block of the DSP task. In this block and also in the following three practice blocks, participants of the experimental group practiced the two previously learned sequences. Participants of the control group received the same practice blocks as those of the experimental group, but their verbally learned sequences did not appear in the practice blocks, since they have learned two sequences that were only relevant for the test phase.

After the first block, the Awareness test took place in which the participants needed to reproduce the sequences of the DSP task by clicking on squares arranged in different manners. Subsequently, all participants had to perform three further practice blocks as well as one test block. The approximate data collection time per participant was 180 minutes.

## Results

### Practice phase

*Reaction times*

By conducting an analysis of variance (ANOVA) with two within-subject factors, Block (4; practice blocks 1-4) and Key (6; keys 1-6), as well as Group (2; experimental group vs. control group) as between-subject factor, it was revealed that most main effects were significant: The main effects of Block, $F(3,66) = 83.2$, $p < .0001$ confirmed an overall difference in reaction times over the blocks, as well as the main effect of Key, $F(5,110) = 282.7$, $p <.0001$. However, there was no main effect of Group, $F(1,22) = 1.7$, $p = .206$, indicating that there is no significant overall difference between the experimental and the control group. Nevertheless, there was an interaction on Block × Key × Group interaction, $F(15, 330) = 7.6$, $p < .0001$, which revealed a significant difference between both groups with respect to reaction times on key presses per block. By taking Fig. 2 into account, a major difference in reaction times per group can be seen in particular on Key 1 of Block 1. The mean reaction time for the experimental group on this key was approximately 1217ms while that of the control group was far higher: 1833ms. Additionally, there is a slight increase for reaction times with respect to Key 4 in Block 1 in both groups, which is in line with the results of the Key × Group interaction, $F(5,110) = 9.0$, $p < .0001$ This increase lessens over the course of the other blocks in the two groups. In line with these results, it was found that the interaction of Block × Key, $F(15,330) = 50.4$, $p < .0001$ was also significant. In short, learning the sequences verbally prior to the experiment especially improved performance on Key 1 in Block 1.

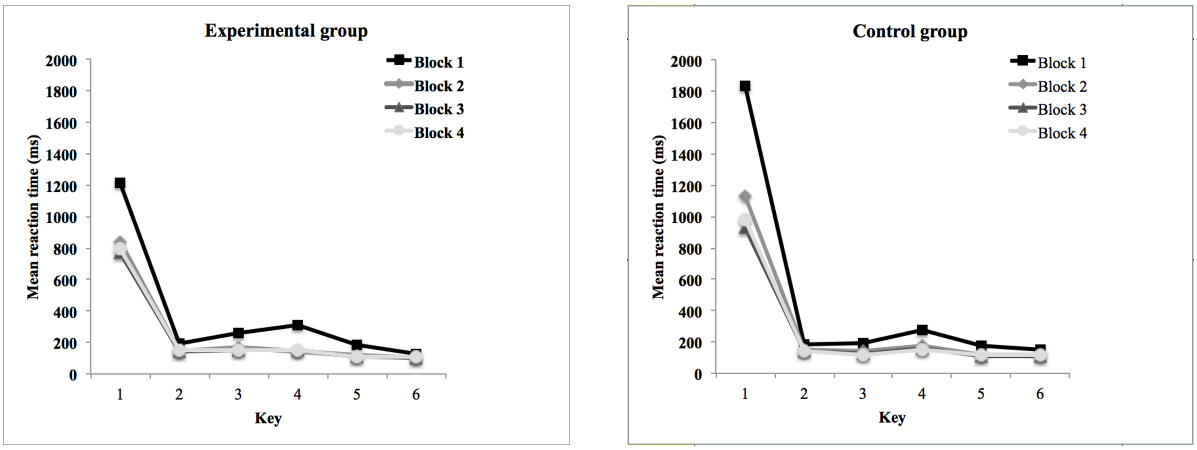


*Figure 2:* Reaction time in the experimental and control group as a function of block and key

*Error rates*

The error rates for the practice phase were transformed by an arcsin transformation and hereafter analyzed with an ANOVA. Here, the same design was used as in the analysis of reaction times described above. The error rates for Block were significant, $F$ (3,66) = 2.9, p = .041, displaying that from block to block, the error rates significantly differed from each other. A closer examination of the particular error rates revealed an increase from block to block: 2.2% (Block 1), 1.8% (Block 2), 2.2% (Block 3) and 2.5% (Block 4). Additionally, a main effect of error rates on Key was found, $F$ (5,110) = 17.0, p < .0001. With respect to the error percentages of Key, most errors were made on Key 3 and 4: 3.2% (Key 3) and 3.3% (Key 4) compared to a mean error rate of 2.2%.

The main effect of Group was not significant, $F$ = (1, 22) = 1.8, p = .193. Further, the only interaction effect that was significant was the Block × Key interaction, $F$ (15, 330) = 2.3, p = .004. With regard to Key 1, error rates increased across the four blocks: 1.9% (Block 1), 2.2% (Block 2) and 2.3% (Block 3 & 4). This tendency was also present for Key 3: 2.6% (Block 1 & 2), 3.5% (Block 3) and 3.9% (Block 4).

**Test phase**

*Reaction times*

For the test phase, another ANOVA was conducted containing Test Condition (3; Conditions: learned sequences, partially learned sequences and new sequences) and Key (6; keys 1-6) as within-subject factors and Group (2; experimental vs. control group) as between-subject factor. The analysis of main effects revealed that two of three main effects were significant: The main effect of Key, $F$ (5,110) = 174.8, p < .0001, as well as the main effect of Test Condition, $F$ (2,44) = 36.0, p < .0001. With respect to the reaction times found across the three test conditions, it can be said that lowest reaction times were found in the practiced sequences condition. Highest reaction times were found in the new sequence conditions, while intermediate reaction times were found in the partially learned sequences condition.

Similarly to the results of the practice phase, the main effect of Group, $F$ (1,22) = .23, p = .634, did not reveal any significant differences between both groups. In line with these results, the Key × Group interaction, $F$ (5,110) = .63, p = .697, was also non-significant. This becomes evident with respect to Fig. 3: the reaction times of both groups resemble each other with a small exception on Key 1. In agreement with the main effect of Key, it becomes apparent that highest reaction times appear on Key 1 and Key 4 in both groups.

The interaction of Test Condition × Key × Group interaction, $F\ (10{,}220) = .23$, $p = .987$, as well as the Test Condition × Group interaction, $F\ (2{,}66) = .10$, $p= .908$, did not reveal any significant difference. With respect to Fig. 4, it can be said that, although there is no significant difference between both groups, the control group has slightly lower reaction times across all three test conditions. This might be statistical support for the potential benefit from the pre-experimental verbal learning for this particular block. The only interaction found to be significant in the test phase is the Test Condition × Key interaction, $F\ (10{,}220) = 16.8$, $p < .0001$.

In short, pre-experimental verbal learning has only minor benefits to sequence learning, since no significant difference between both groups was found. However, motor sequence knowledge of pieces of the learned sequences supports performance: This becomes evident with respect to the main effect of Test Condition, as well as Fig. 4.

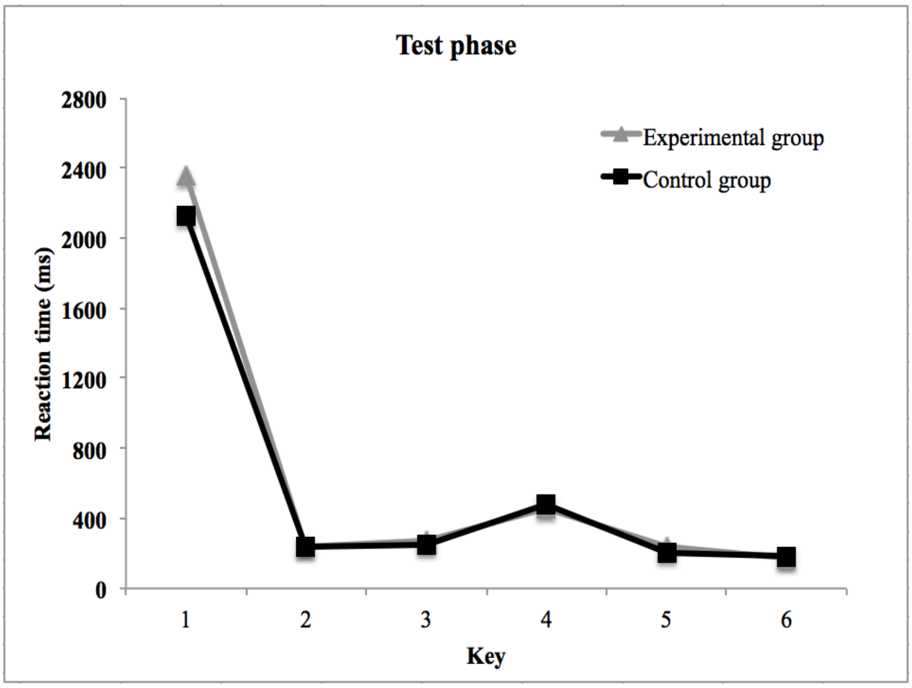


*Figure 3:* **Reaction times per key press**

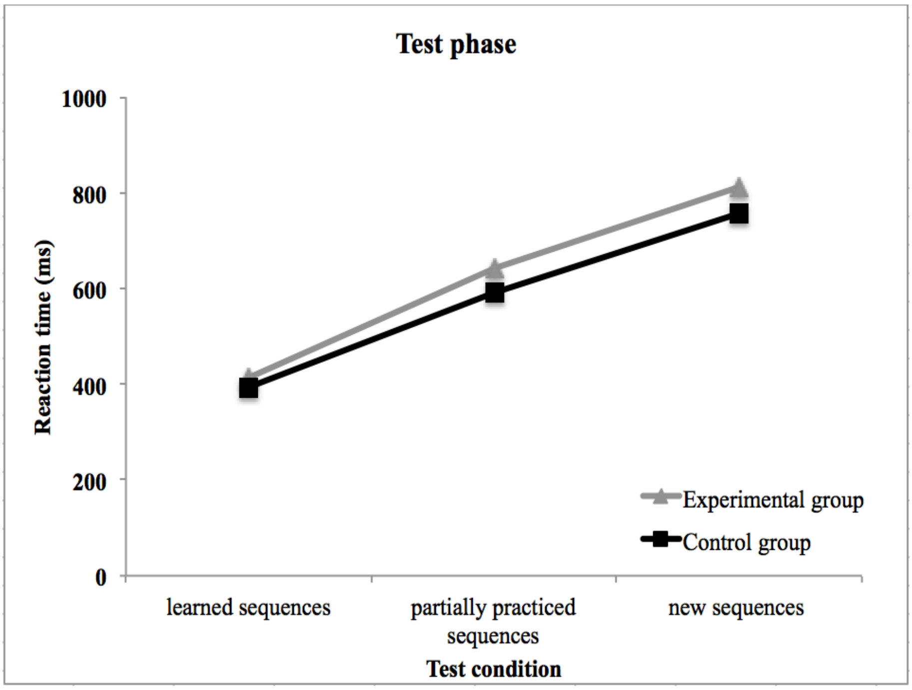


*Figure 4*: **Reaction time difference across test conditions**

*Error rates*

As with the error rates of the practice blocks, an arcsin transformation was performed for the error proportions of the test phase. An ANOVA with repeated measures was performed hereafter. The error rates of Key, $F$ (5,110) = 14.7, $p < .0001$, were significant, showing especially an increase in error rates from Key 3, 4.3%, to Key 4, 8.1%.

A significance on percentages of error rates of Test Condition, $F$ (2,44) = 7.8, $p = .001$, implies significant differences between the three different test conditions. Lowest error rates with a value 2.8% was found in the 'learned sequence' Condition. Intermediate error rates with a value of 3.8% were found in the 'partially learned sequence' Condition, where participants knew pieces of the sequence. As expected, the highest error rates were found in the 'new sequence' Condition: 5.1%. Also, the difference between error rates of Group was found to be significant, $F$ (1,22) = 6.2, $p = .021$, with an overall error value of 4.7% for the control and 3.1% for the experimental group. In contrast to this, when examining the Test Condition × Group interaction, $F$ (2,44) = 1.1, $p = .354$, it was found that there was no significant difference in error rates between the two groups.

Accordingly, the Key × Group interaction, $F$ (5, 110) = 1.5, p = .186, also revealed no significant differences in error rates, as well as the Test Condition × Key × Group interaction, $F$ (10, 220) = 1.3, p = .233. The only significant interaction has been found in Test Condition × Key, $F$ (10, 220) = 3.0, p = .002. Closer views at the percentages of error rates revealed that especially the responses of Key 4 were a stable source of errors when compared with the rest of the response errors: 4.8% ('learned sequence' Condition), 7.1% ('partially learned sequence' Condition) and 12.2% ('new sequence' Condition) compared respectively to a mean error rate of 2.78% ('learned sequence' Condition), 3.87% ('partially learned sequence' Condition) and 5.12% ('new sequence' Condition).

**Awareness test**

To analyze the results of the Awareness test, a chi-square test was conducted to compare the results of both groups on sequence reproduction.

*Verbal representation*

The verbal representation of the Awareness test included participants to respond to the six squares containing the letters of the sequences in a circle. They needed to identify the correct order for both sequences as accurate as possible by clicking on them. The differences in the verbal representation are determined by analyzing the correctness of answers given by all participants of both groups. The analysis revealed that the performance on verbal representations of both groups did not significantly differ from each other, $\chi^2$ (2) = 1.835, $P$ = .399. A greater number of participants of the experimental group could recall two sequences, when compared to the number of participants of the control group: 8 (66.7%) compared to 5 (41.7%), respectively. Therefore, a smaller number of participants of the experimental group had difficulty with recalling any sequence at all when compared to those of the control group: 1 (8.3%) compared to 3 (25%), respectively. However, these differences in percentages per group did not represent any significant differences in the analysis.

*Spatial representation*

Similarly to the approach of the analysis of the verbal representation, a chi-square test was conducted to analyze the spatial representation test performance of both groups.

The spatial representation was examined by asking participants to click in the correct order on the squares in a row. In this task, the squares contained no letters.

Here, in contrast to the findings of the verbal representation analysis, the analysis revealed a significant difference between the experimental and control group, $\chi^2$ (2) = 6.349, *P* = .042. When comparing the percentages of both groups, it becomes apparent that the most striking differences are found in the correctness of none and two sequences. While 7 (58.3%) participants of the experimental group could not recall any sequence during this Awareness task, only 2 (16.7%) participants of the control group had difficulty with this. In line with these results, 6 (50%) participants of the control group could recall both sequences requested while this was only possible for 1 (8.3%) participant of the experimental group. An equal number of participants of both groups could recall one sequence of the two equally: 4 (33.3%).

## Discussion

The main goal of this study was to examine the effects of pre-experimental verbal learning of two given letter series on motor sequence performance in a classical DSP task. Participants performed the DSP task either using the previously verbally learned sequences (experimental group) or two new sequences (control group) across the four practice blocks. First, the study was aimed at investigating whether pre-experimental verbal learning of the two sequences supported sequence learning in the DSP task in general. Additionally, participants were given one test block containing three conditions, whose purpose was to examine the effects of pre-experimental verbal learning on these: the practiced sequence condition, the partially learned sequence condition and the new sequence condition.

With respect to the literature, it was expected that the participants of the experimental group would benefit from the pre-experimental verbal learning. Reaction times of these participants were predicted to be lower than those of the control group due to them being able to generate chunking patterns more quickly during the course of the experiment because of their verbal sequence knowledge. Also, it was expected that this benefit would vanish across the practice blocks due to the ability of all participants to develop motor chunks. With regard to the test block, however, it was predicted that the control group would outperform the experimental group especially in the partially learned sequence condition. This was anticipated because the participants of the control group generated sequence knowledge spatially as well as verbally. Their knowledge included verbal chunks on the whole sequences, whereas participants of the experimental group only established verbal chunks on parts of the sequences. Both groups' spatial knowledge contained motor chunks for parts of the two sequences. With respect to the Awareness test of this study, it was expected that participants of the experimental group would outperform participants of the control group with respect to the verbal part of the Awareness test due to their pre-experimental verbal sequence representation established prior to the experiment. In the spatial part of the Awareness test, the contrary was expected: Participants of the control group should have generated better spatial sequence knowledge.

The results of this study were varying with respect to the verification of the predictions above. With reference to the first hypothesis, there was, indeed, a pre-experimental verbal learning effect for the experimental group found in lower reaction times when compared to those of the control group. As expected, this did not appear to be an overall phenomenon of performance of the experimental group, for there was no overall significant difference in reaction times for both groups. The only difference between both groups was registered on the responses of Key 1 in Block 1: Participants of the experimental group were significantly quicker on reacting to the upcoming stimuli than the participants of the control group. This effect is assumed to be due to the fact the participants of the experimental group had the possibility to generate verbal chunks prior to the experiment. This enabled them to react quicker because it took them less time to memorize the letter sequences appearing on the screen before being able to press the first key. Participants of the control group, though, had to memorize the sequences more attentively, which in turn was more time consuming and therefore resulted in higher reaction times for the control group on Key 1 of Block 1.

With reference to the DPM of Verwey (2001), participants of the experimental group are assumed to have generated first connections between the developed chunks due to their pre-experimental verbal learning (Ruitenberg et al., 2014). The cognitive processor is therefore considered to be able to load the motor buffer with the required responses more quickly. Participants of the control group, though, generated no such connections. Therefore, the cognitive processor must load each response one by one into the motor buffer, which leads to lower performance rates (Abrahamse et al., 2013). As expected though, this effect vanished over the course of the other three blocks resulting in a non-significant difference between both groups, as mentioned earlier.

Another interesting phenomenon has been detected in this experiment with respect to Fig. 2: It was found that both groups similarly had higher reaction times on Key 4 when comparing them to those of the other keys (except for Key 1). This phenomenon appeared in particular in Block 1. Abrahamse et al. (2013) argued that the number of responses held in the chunk would increase with ongoing practice. Therefore, the longer reaction times on Key 4 might represent the beginning of a new motor chunk. With more extensive practice, this second motor chunk is assumed to be connected to the first, which is statistically supported by the decrease in reaction times on Key 4 with respect to ongoing blocks.

Taking into account the results of the test phase, it can be mentioned that there was indeed a significant decrease in performance with respect all three test conditions. This drop in performance from one to the other could be explained by taking into account how much sequence knowledge participants had per condition: the learned sequences could be performed quickly and autonomously because of their prior practice. In the partially learned sequence test condition, participants of the experimental group had verbal as well as motor chunks on *parts* of the sequences. The control group also had motor sequence knowledge on parts of the sequences, but they also established verbal sequence knowledge on the *whole* sequences prior to the experiment. This advantage resulted in a slightly better performance, which can be seen in Fig. 4, although the analysis revealed no significant difference between groups. The new sequence test condition took participants the longest to be accomplished, for they had no sequence knowledge on the sequences at all.

With reference to the DPM and Fig. 4, it is assumed that participants switch backwards through the different modes of sequence learning with respect to the three conditions. In the practiced sequence test conditions, participants are assumed to be in the chunking mode of the model: They have established motor chunks and task performance is accomplished very much autonomously without greater cognitive involvement (Tracy, Pinsk, Helverson, Urban, Dietz & Smith, 2001; Gasbarri, Pompili, Packard & Tomaz, 2014). When receiving the unknown sequences, participants are no longer able to automatically type the sequence in. They need to consciously attend the given stimuli one by one before being able to react. These sequence performance characteristics resemble those of the reaction mode of the DPM: the cognitive processor loads the motor buffer one by one, resulting in slow execution rates in this test condition (Abrahamse et al.,2013; Ruitenberg et al., 2014). However, when looking at the partially learned sequences, participants' performance is better than what it is assumed to be in the associative mode, because they already make use of motor chunks. This is especially supported by the particular higher reaction times that have been found on Key 4 for both groups, while those for Key 2 and 3, as well as Key 5 and 6, are lower (see Fig. 3). This implies that participants benefit from the generated motor chunks. However, the disrupted arrangement is responsible for the disability of the cognitive processor to program the motor processor with the whole sequence at once.

Taking the results of the Awareness test into account, it becomes apparent that the results have only partly met the expectations. The analysis of the *verbal* Awareness test revealed no significant difference in performance between both groups with respect to being able to memorize the sequences. The verbal representation of the sequences was similar in both groups. One could speculate that either pre-experimental verbal learning had no supportive effects on the performance of the Awareness test. Also, it could be that the verbal representations were replaced by spatial representations during the first practice block of the DSP task. When taking the results of the *spatial* Awareness task into account, the analysis revealed that participants of the control group did indeed outperform those of the experimental group. It could be hypothesized that this effect is due to the fact that the verbal representations in the latter group might have hindered the building of spatial representations. Nevertheless, the results of the Awareness test revealed a point of concern regarding the procedure of this test: Participants were required not to look on the keyboard during the test. Yet, one question of the test disclosed that some participant did in fact look on the keyboard while reproducing the sequences. It might be that the results of the verbal and spatial analysis therefore incorporate little reliability. Future research should hence take this into account and should apply changes to the procedure of the experiment.

What now can be concluded from this research is that verbal sequence knowledge indeed supports motor sequence learning. However, this support is only given within short times, namely in the first block of trials. Across several practice blocks, the effect vanishes due to sufficient practice and the development of motor chunks on the sequences. With regard to verbal sequence knowledge on the whole sequences and motor sequence knowledge on parts of sequences, it can be said that motor sequence knowledge is an important benefit for sequence performance: It helps enhancing and improving performance. Verbal sequence knowledge, though, has only minor effects on sequence performance. Its effects are rather gradual, but still, it enhances performance slightly.

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*Figure 1 – Computer icon*

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*Figure 1 – Hand icons*

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# Appendix

## Appendix I

*Experimental group*

| Participant | sequences verbally learned | | practice & test: learned sequences | | test: partially learned sequences | | test: new sequences | |
|---|---|---|---|---|---|---|---|---|
| | *Verbal1* | *Verbal2* | *DSP1* | *DSP2* | *DSP3* | *DSP4* | *DSP5* | *DSP6* |
| 1 7 | kfgdjl | fkljdg | kfgdjl | fkljdg | djl-fkl | jdg-kfg | lgj-fk-d | gld-kf-j |
| 2 8 | lgjfkd | gldkfj | lgjfkd | gldkfj | fkd-gld | kfj-lgj | djk-gl-f | jdf-lg-k |
| 3 9 | djkglf | jdflgk | djkglf | jdflgk | glf-jdf | lgk-djk | fkl-jd-g | kfg-dj-l |
| 4 10 | fkljdg | kfgdjl | fkljdg | kfgdjl | jdg-kfg | djl-fkl | gld-kf-j | lgj-fk-d |
| 5 11 | gldkfj | lgjfkd | gldkfj | lgjfkd | kfj-lgj | fkd-gld | jdf-lg-k | djk-gl-f |
| 6 12 | jdflgk | djkglf | jdflgk | djkglf | lgk-djk | glf-jdf | kfg-dj-l | fkl-jd-g |

*Control group*

| Participant | sequences verbally learned | | practice & test: learned sequences | | test: partially learned sequences | | test: new sequences | |
|---|---|---|---|---|---|---|---|---|
| | *Verbal1* | *Verbal2* | *DSP1* | *DSP2* | *DSP3* | *DSP4* | *DSP5* | *DSP6* |
| 13 19 | djlfkl | jdgkfg | kfgdjl | fkljdg | djl-fkl | jdg-kfg | lgj-fk-d | gld-kf-j |
| 14 20 | fkdgld | kfjlgj | lgjfkd | gldkfj | fkd-gld | kfj-lgj | djk-gl-f | jdf-lg-k |
| 15 21 | glfjdf | lgkdjk | djkglf | jdflgk | glf-jdf | lgk-djk | fkl-jd-g | kfg-dj-l |
| 16 22 | jdgkfg | djlfkl | fkljdg | kfgdjl | jdg-kfg | djl-fkl | gld-kf-j | lgj-fk-d |
| 17 23 | kfjlgj | fkdgld | gldkfj | lgjfkd | kfj-lgj | fkd-gld | jdf-lg-k | djk-gl-f |
| 18 24 | lgkdjk | glfjdf | jdflgk | djkglf | lgk-djk | glf-jdf | kfg-dj-l | fkl-jd-g |