The effect of sequential motor learning on cognitive control

Jan Papenfuß (s1084887)

Faculty of Behavioral Sciences, University of Twente, the Netherlands

In fulfillment of the Bachelor's thesis requirement

Psychology

1st Supervisor: Dr. Marit Ruitenberg

2nd Supervisor: Dr. Elian de Kleine

June 17, 2013

Table of Contents

Abstract

The aim of this study was to find out if automatic motor learning could enhance cognitive control. Sixteen students of the University of Twente completed a combination of the Discrete Sequence Production (DSP) Task and the Stroop Task. In a regular Stroop Task, participants respond to the ink of a color word, while ignoring the word's meaning. In addition, in this experiment, participants also unknowingly practiced two underlying sequences over six blocks. After completing the practice phase, they were confronted with two new, unfamiliar sequences in the test phase. It was observed that Stroop effect became smaller as the sequence was practiced more often. Further and more importantly, results demonstrated that the Stroop effect recovered when participants were confronted with unfamiliar sequences. We found no indications for a relationship between sequence awareness and magnitude of the Stroop effect. Moreover, the results support the Dual Processor Model of sequential motor learning. Taken together, these findings indicate that motor sequence learning can enhance cognitive control. Further research could focus on generalizing these findings to other cognitive conflict tasks, investigating whether Stroop effect would disappear if the practice phase was extended, researching the effect of implicit motor learning on cognitive control, or focus whether cognitive conflict improves sequential motor learning.

Introduction

Every day, we are carrying out several same actions again and again. Your daily morning routine, the way you put on a jacket or the way you tie your shoelaces are actions that are carried out automatically. They are learned over years of practice. Through practice or repetition, they eventually became automatic. Through this process, which is referred to as motor learning, you do not have to waste much thought on what you are doing. But carrying out automatic motor actions does involve a cognitive aspect. Picture inviting friends over for coffee: You prepare a beautiful cake that you want to bring to the dining room. On the way there, the cake slips out of your hand. What would you do? You would probably try everything to prevent the cake from falling down because otherwise the get-together with your friends would be ruined. Now imagine, you are carrying a hot cup of tea and the same thing happens. The reaction to dropping the cup of tea would probably be very different, since you could seriously burn yourself. A cognitive conflict arises whether to try to catch the cup or let it fall. In the blink of an eye, you would step back to protect yourself. This illustrates the importance of cognitive control while carrying out actions, even if they are automatic. Such cognitive (or executive) control allows us to flexibly alter thoughts and behaviors that would otherwise be carried out automatically. Important aspects of the control processes are initiation, inhibition, task switching, and monitoring (Purves et al., 2008). This research paper focuses on the interplay between automatic and cognitively controlled actions. Specifically, the focus lies on the possible effects of sequential motor learning on the aspect inhibition of cognitive control.

A famous paradigm for investigating cognitive control is the Stroop task. It generates an artificial conflict situation in which cognitive control processes are needed to solve this conflict**.** In the Stroop task, participants are confronted with a color word stimulus: They have to name the color in which a color word is written, while ignoring the meaning of the word itself. The trials can either be congruent (the color of the word corresponds with the meaning of the word, e.g., red written in the color red) or incongruent (the color of the word does not correspond the meaning of the word, e.g., red written in the color blue). In the incongruent trials, the difference between word meaning and word ink results in a cognitive conflict. Participants experience problems in naming the color of the word because reading it is the dominant or automatic response to a word (and not perceiving color; Botvinick, Braver, Barch, Carter, & Cohen, 2001). The response time to successfully identify the color of the word in incongruent trials is usually longer than in congruent trials. That is called the Stroop effect and shows that carrying out cognitive control (i.e., inhibiting the reading response) takes time and demands cognitive resources (Deroost, Vandenbossche, Zeischka, Coomans & Soetens, 2012; Purves et al., 2008). More cognitive control is represented by a smaller Stroop effect due to a smaller difference in response time between incongruent and congruent trials. The decrease of this difference between congruent and incongruent trials in a conflict task is explained by an increase in the efficiency of processing task relevant information elicited by cognitive adaptation to the task (Deroost et al., 2012).

Deroost et al. (2012) observed that perceptual sequence learning in high conflict situations supports and increases cognitive control, more particularly conflict resolution. They developed a version of the Stroop task, in which the participants learned a sequence. Like in a normal Stroop task, participants were asked to name the ink while ignoring the meaning of the word. Unlike a normal Stroop task, Deroost et al. presented the word color in a probabilistic sequence. The participants were not informed about the underlying sequence. As such, Deroost and colleagues could determine if participants who learned a sequence, become better in solving the conflict in the Stroop task. The results of the experiment showed a training effect that lead to a gradual decrease of the Stroop effect. The authors interpreted this result as improvement of the participants' anticipation of the following word color. Ultimately, at the end of the experiment participants were able to completely overcome the Stroop effect. When the participants were confronted with an unknown sequence afterwards, the Stroop effect recovered fully. Based on these findings, Deroost and colleagues argue that automatisms enhance cognitive control, thus conflict resolution. This implies that automatisms protect against or at least decrease the Stroop effect.

Other studies with conflict tasks also show that sequence learning processes improve cognitive control (Koch, 2007; Tubau & López-Moliner, 2004). The difference to the study of Deroost et al. (2012) is that conflict reduction only occurred when the sequences were learned explicitly. Tubau and López-Moliner (2004) found that explicit learning of motor sequences reduces Simon-like conflict. In their study, they made use of the Simon task in which participants are asked to respond to the meaning of a letter presented, while ignoring the location where it was presented. Either the letter E or D was shown, meaning that participants had to respond by clicking the button on their left or right side, respectively. By using the Sequence Response Task, Tubau and López-Moliner presented the stimuli in certain sequences. One group of the participants was informed about the underlying sequences, while the other was not. Tubau and López-Moliner reported that the differences in response time between incongruent trials and congruent trials were smaller when there was an underlying sequence than when there was no underlying sequence. In another study, Koch (2007) reported that explicit sequence learning could lead to motor chunking, which improves solving cognitive conflicts in a Simon task. Motor chunking describes the transition from stimulus-based motor control to memory-based motor control. That means that a series of movements is represented in a single memory representation (Ruitenberg, Abrahamse & Verwey, 2013). We elaborate further on this below. As a result, motor chunking should reduce the effect of stimulus information on motor performance and therefore reduce cognitive conflict. Koch carried out three experiments using a serial four-choice reaction-time task to investigate the relationships of motor sequence learning and stimulus based-response conflict. Taken together, these studies demonstrate a positive effect of motor sequence learning on cognitive control mechanisms. More specifically, they show that sequential learning processes can help individuals to deal with conflicting information more effectively.

A possibility to investigate the development of motor sequences is the Discrete Sequence Production (DSP task). It is based on the assumption that complex motor actions of everyday life (i.e. tying shoelaces) consist of discrete movement sequences. The DSP task represents the way in which sequential actions are acquired (Ruitenberg et al., 2013). In the DSP, participants usually practice discrete (i.e., brief) sequences by responding to a constant series of three to six key-specific stimuli (for a recent overview, see Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013). The participants' task is to react to one of four horizontally aligned stimuli by means of a spatially compatible key press. The stimuli are presented in a fixed order. The more the participants practice, the less cues are needed to solve the conflict that arises from the presented stimuli. With the presentation of the first cue, it triggers the response for the entire sequence (Ruitenberg, De Kleine, Van der Lubbe, Verwey & Abrahamse, 2012; Verwey, 2010; Verwey, Abrahamse, Ruitenberg, Jiménez & De Kleine, 2011; Verwey & Wright, 2004).

Based on research with the DSP task, a Dual Processor Model has been developed (Abrahamse et al., 2013). It states that a cognitive and a motor processer are responsible for learning discrete movements. The task of the cognitive processer is the transition from a single stimulus into the respective response. It is predominately active during early practice and triggers the motor processor, which is responsible for carrying out the respective action, to execute the response for each stimulus separately. Another possibility is that, if the sequences are explicitly known, the cognitive processer loads a limited number of individual responses into the motor buffer which is a part of working memory. After practicing a series of movements repeatedly, it is assumed that these sequences are integrated into a single representation, leading to a motor chunk. Then, instead of loading every stimulus individually into the motor buffer, a motor chunk is loaded which constitutes a single response of several actions. Motor chunks can be prepared in advance and lead to a faster execution of sequential movements. After extensive practice, even longer sequences of movements are grouped into several chunks that make up our everyday learned behavior. In line with the DPM, Verwey (2003) points out that at least two execution modes exist. Firstly, there is a reaction mode in which sequences are generated based on key-specific stimuli information that involves closed-loop control. Secondly, in the chunking mode, a key-specific stimuli information is no longer needed and the mode can be described as rather open-loop controlled.

Taken together, earlier studies found that sequential learning improves cognitive control (e.g., Deroost et al., 2012; Koch, 2007; Tubau & López-Moliner, 2004). Since the study of Deroost et al. is the first to show the influence of perceptual sequential learning on cognitive learning without the necessity of being aware of the learning process, further research on this topic is still lacking. Moreover, research on whether motor sequence learning could enhance conflict resolution in participants that were not explicitly informed about the sequential order of the stimuli is also lacking. For that reason, this study not only seeks to broaden the knowledge about the relationship between sequential learning and cognitive control, but it also seeks to gain more insights on the effect of motor sequence learning on cognitive control in participants that are not informed about underlying sequences.

In the present study we combine the Stroop task with the Discrete Sequence Production task. Differently colored Stroop words are displayed in a certain sequence (e.g., red, blue, red, yellow, green). Each color stands for one respective finger. Participants still have to perform constant sequences of key presses as in the DSP task, but responses depend on the ink color of the word. Participants learn this sequence. In a normal version of such a motor learning task, the ongoing repetition of a sequence leads to a shorter reaction time (Purves et al., 2008). We investigated the influence of sequential motor learning on cognitive control by first looking if Stroop effect decreases over practice and second looking if the Stroop effect is smaller in familiar sequences than in unfamiliar sequences.

In sum, previous studies suggest that automatic motor learning processes improve cognitive control, but extensive research in this field is lacking. The aim of this study is to find out more about the interaction between cognitive control and motor learning. More specifically, we examine whether sequential motor learning could enhance cognitive control. With the help of the DSP task, participants learn fixed sequences of key presses of which the participants are unaware. It is hypothesized that participants who would practice a sequence would show smaller Stroop effects. Another hypothesis is, that participants show smaller Stroop effects when they perform familiar sequences than when they perform unfamiliar sequences. A decrease in Stroop effect would be an indication for higher cognitive control.

Method

Participants

Sixteen students (7 female and 9 male, *M* age = 22.25 years, *SD* = 1.65 years) from the University Twente participated in the experiment. In exchange for their participation, they were rewarded with course credits. All sixteen participants were right-handed according to Annett's (1970) Handedness Inventory. Restrictions for participation were that all participants needed to have German as their mother tongue, had no motoric disability in their arms and hands, had normal vision, and were not colorblind. The study was approved by the ethical committee of the Faculty of Behavioral Sciences of the University of Twente.

Apparatus

The participants completed the task on an Intel Core i7-3770 (4*3.400 MHz) personal computer with 8GB RAM running under Windows 7 in the lean mode (i.e., all processes that could possibly affect reaction time measurement were switched off). Stimuli were presented on a 22-inch LG Flatron Monitor in normal daylight settings in different, but homogenous rooms in the laboratory of the University of Twente. For stimulus presentation and data collection, E-Prime software (version 2.0) was used.

Task and Procedure

Before beginning the actual experiment, participants were asked to give their informed consent and fill out Annett's (1970) Handedness Inventory. Next, they were provided with detailed information about the procedure of the experiment and were informed that they could be supervised via camera in an upper corner of the room. If the participant made clear that he/she understood the instruction completely and correctly, the experimenter would start the program and leave the room.

The experiment was conducted in German. As in a classical Stroop task, participants were confronted with color words (i.e., “Rot” = red, “Blau” = blue, “Gelb” = yellow, “Grün” = green) written in one of the ink colors blue, green, yellow or red. In a congruent trial, the ink of the color word resembled its meaning. In an incongruent trial, the ink in which the word is written differs from the meaning of the word. The participants were instructed to respond as fast and accurate as possible to the ink of the color word, while rejecting its meaning. They were asked to respond with their index and middle fingers of both hands by using the keys C, V, B, and N. The keys C, V, B, and N indicated whether the ink of the color word was red, green, yellow, or blue, respectively. To lessen the cognitive load of remembering the different keys for each color, a piece of paper with the respective colors from left to right was placed at the bottom of the monitor. The stimuli were presented in the center of the screen, in Courier New in a font size of 18. The Stroop stimuli were always presented in two constant sequences. A correct answer was given when a participant accurately identified the ink of the color word by pressing the appropriate key. A wrong answer by participants was followed by an error message (“Falsch”) for 1.000 ms and then the same stimulus was presented again until the participant gave the correct answer. If participants made a premature response, they received a message indicating that their response was too early (“Zu früh”) and then the next sequence started.

The experiment consisted of a practice phase and a test phase. The practice phase was made up of six blocks in which participants were always confronted with the same two sequences. The test phase consisted of two blocks, one in which the participants performed the two familiar sequences from the practice phase and another one in which they performed two unfamiliar sequences. In both the practice phase and test phase, participants were confronted with 50% congruent and 50% incongruent stimuli.

Altogether, there were two sequence structures that were each subdivided in four further sequences, leading to eight sequences in total. Each participant only learned two of the eight sequences in the practice phase. In the test phase, participants were once again confronted with the two familiar sequences from the practice phase but in addition to that, they also completed a block in which they encountered two completely unknown sequences. In sum, they learned two sequences over six practice blocks and then they completed one familiar and one unfamiliar block. The test phase with familiar and unfamiliar sequences was counterbalanced. In condition one, participants learned the sequences “ncbvbc” and “vnbcnv”. In conditions two, three and four, they learned the sequences “bnvcvn” and “cbvnbc”, “vbcncb” and “nvcbvn”, and “cvnbnv” and “bcnvcb”, respectively. The sequences themselves were counterbalanced as well, meaning that every finger was used equally often over different participants. Further, a restriction was that participants never practiced two sequences that begin with the same finger so that one finger would only be responsible for triggering one sequence.

The experiment started with an on-screen message that repeated the placement of the fingers, after which the participants could start the first block. A block consisted of 48 trials (i.e., 24 trials per sequence) and the sequences were presented in random order. A sequence consisted of six key-presses that were followed by the appearance of a white cross in the middle of the screen (see Figure 1). Participants received a short break of 30 seconds after 24 trials. After this short break, they completed another set of 24 sequences. Then, they received a longer break and the program shut down automatically. Participants were instructed to ask the researcher to start the next block. After that, this cycle was repeated eight times, after which all blocks were completed.

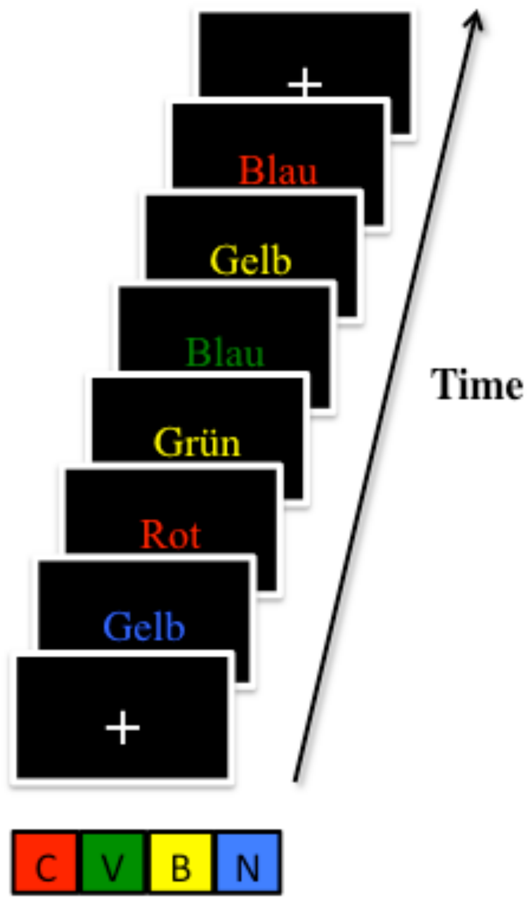

Figure 1. Example of one trial for the sequence “ncbvbc”

At the end of the experiment, after finishing both test blocks, participants were asked to fill out a questionnaire to measure their awareness (i.e., explicit knowledge) of the sequences. Firstly, it was asked if they were able to recall the two sequences they had learned during the experiment explicitly and then, to write them down. Secondly, it was examined if they could recognize the two learned sequences out of twelve possibilities. At the end of the questionnaire, participants were asked to report whether they were familiar with a sequence-task, one or both sequences and if they had any comment on the procedure and the study itself.

Data analysis

To examine the effects of motor sequence learning on cognitive control, the change of Stroop effect over practice (practice phase) and the difference between Stroop effect in familiar and unfamiliar conditions (test phase) were determined. The goal of determining the effect of the practice phase was to determine whether Stroop effect would decrease over the six practice blocks. A decrease in performance can be attributed not only to motor sequence learning, but also to general learning. Thus, the analysis of the practice phase provides information about sequence learning and general learning and therefore, the investigation of the test phase serves as crucial measure. The participants' performance on the task should be worse on blocks with unfamiliar sequences in comparison to blocks with familiar sequences. If motor sequence learning improves cognitive control, as hypothesized, the Stroop effect is expected to be larger when the sequences are unfamiliar than when they are familiar. In addition, it will be examined whether sequence awareness in the form of recall and recognition is related to a smaller Stroop effect.

Results

Practice Phase

Reaction Time

Results of a mixed analysis of variance (ANOVA) with Congruency (2; congruent vs. incongruent) and Block (6; practice blocks one to six) as within-subject factors showed a main effect of Congruency, $F(1, 15) = 80.36$, $p < .001$. Specifically, reaction times were higher on incongruent trials than on congruent trials (536ms vs. 506ms). This confirmed the Stroop effect. Moreover, there was a main effect of Blocks which indicated that reaction times decreased over the practice blocks, $F(5, 75) = 46.28$, $p < .001$ (cf. Figure 2). A Congruency x Block interaction was also found, indicating that Stroop effect diminished significantly over blocks, $F(5, 75) = 2.75$, $p = .025$. In addition, two separate repeated measures ANOVA's, one for Block 1 and one for Block 6, were carried out in order to determine if the Stroop effect had diminished fully at the end of the practice phase. Results showed that the difference between incongruent and congruent trials was significant in both Block 1 (693ms vs. 642ms), $F(1, 15) = 35.13$, $p < .001$, and Block 6 (422ms vs. 401ms), $F(1, 15) = 17.63$, $p < 0.001$. This suggests that the Stroop effect was not overcome completely, but did decrease over time. These effects are displayed in Figure 2.

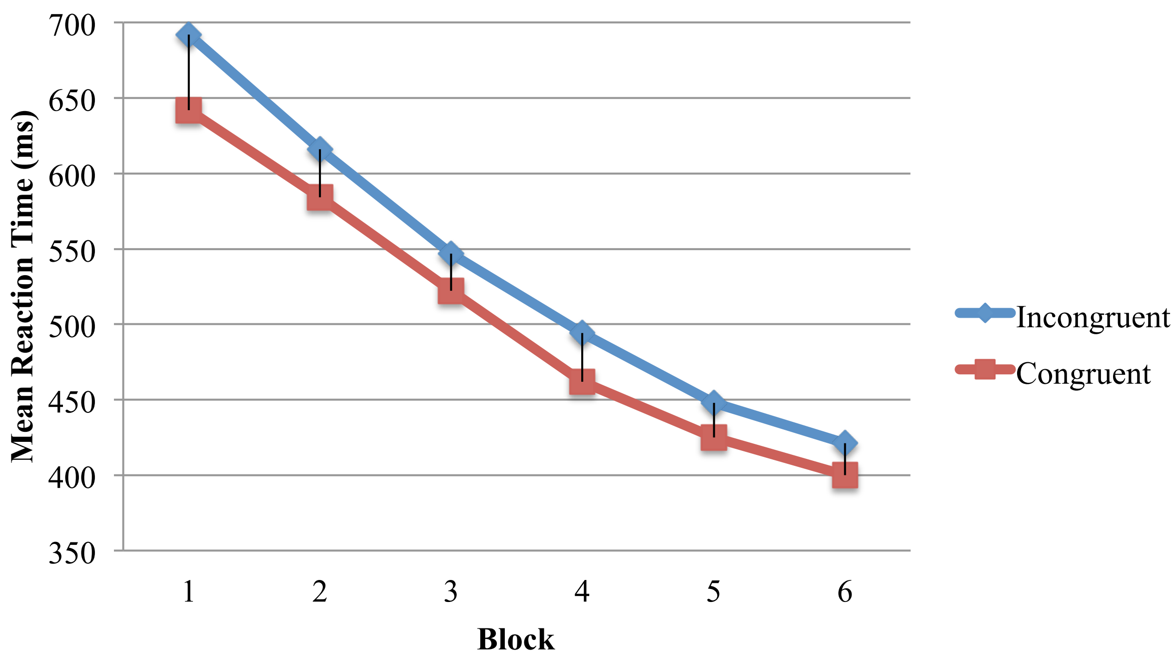

Figure 2. Mean reaction times (in milliseconds) as a function of congruency and block in the practice phase

Errors

In the practice phase, participants made few errors in both congruent (M =3.32%, SD = 1.02) and incongruent trials (M = 3.00%, SD = 1.45). These relatively low error percentages indicate that the task was completed accurately. The analysis of the error rates did not reveal any significant effects of Congruency, Blocks or an interaction between them (ps > .17). That means that error rates were comparable between incongruent trials and congruent trials as well as that they were comparable over the different blocks.

Test Phase

Reaction Time

To determine the motor-sequence learning effect, reaction times of the two test blocks were analyzed by running a repeated measures ANOVA with Congruency (2) and Test block (2; familiar vs. unfamiliar) as within-subject factors. Like in the practice phase, a main effect of Congruency showed that reaction time was generally shorter on congruent trials in comparison to incongruent trials (475ms vs. 497ms), $F(1, 14) = 21.48$, $p < .001$. Additionally, a main effect of the Test block shows that participants needed more time to execute their sequences in the unfamiliar block than in the familiar block (586ms vs. 386ms), $F(1, 15) = 57.53$, $p < .001$. Again, an interaction effect was found between Congruency and Test block, $F(1, 15) = 4.53$, $p = .05$. It shows that Stroop effect was larger for the unfamiliar sequences in comparison to the familiar sequences (see Figure 3). Two separate repeated measures ANOVA's, one for the familiar and one for the unfamiliar sequences, were carried out to determine the Stroop effect for each separately. Main effects were found for both, familiar, $F(1, 15) = 6.78$, $p = .020$, and unfamiliar sequences, $F(1, 15) = 6.78$, $p < .001$, indicating that there were significant differences in both the familiar and unfamiliar test blocks.

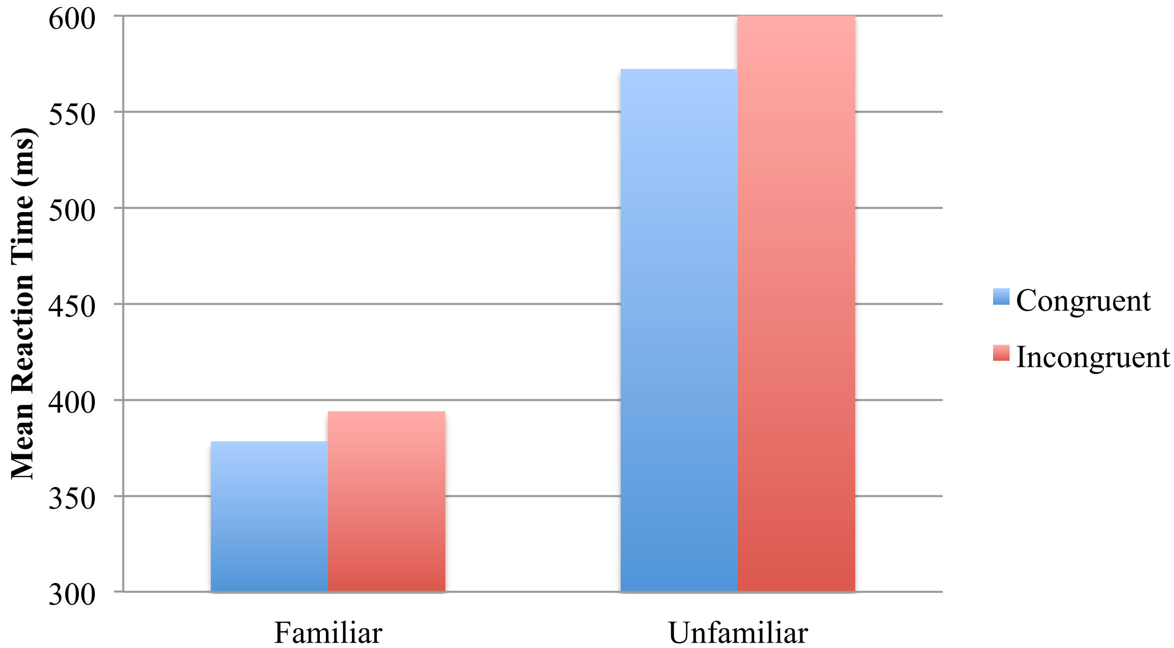

Figure 3. Mean reaction times (in milliseconds) as a function of congruency and familiarity in the test phase

Errors

The analysis of the error percentages showed a main effect of congruency, $F(1, 15) = 4.49$, $p = .050$. It illustrates that there is a significant difference between incongruent and congruent trials, specifically, that fewer errors were made when stimuli were congruent ($M = 2.86\%$, $SD = .38$) than when they were incongruent ($M = 3.56\%$, $SD = .41$). Further, a main effect between familiar and unfamiliar blocks could be found, $F(1, 15) = 20.08$, $p < .001$. It shows that fewer errors were made in the familiar block ($M = 2.38\%$, $SD = .33$) than in the unfamiliar block ($M = 4.03\%$, $SD = .47$). There was no interaction between Congruency and Block ($p = .17$).

Awareness

Results of the awareness questionnaire showed that seven participants (44%) correctly recalled both their practiced sequences and that nine participants (56%) could not recall any sequence. In addition, in order to integrate participants that could not report the sequence completely, it was analyzed how many digits of a sequence every participant was able to report (M = 8.19, SD = 3.78). Every participant reported at least three of the twelve digits correctly. Further analysis showed that nine participants (56%) recognized both their practice sequences, while five participants (31%) recognized one sequence and two participants (13%) could not recognize either of the two sequences. A correlation analysis between the recall, the number of digits recalled correctly, recognition, and Stroop effect (the difference in reaction time between incongruent and congruent trials) was carried out in order to see if sequence awareness and Stroop effect are related. No significant correlation between the three awareness elements and Stroop effect was found (ps > .26), suggesting that the degree of explicit sequence knowledge and the size of the Stroop effect were not related to each other.

Discussion

The present study examined if automatic motor learning can enhance cognitive control. To this end, we investigated if the learning of a motor sequence on the basis of Stroop stimuli would lead to a smaller Stroop effect and thus, greater cognitive control. Moreover, it was investigated if familiarity with the sequence leads to greater cognitive control as compared to control in an unfamiliar sequence. As hypothesized, the results of this study showed that the Stroop effect decreased steadily over practice and thus indicated cognitive control increases by learning a motor sequence. It can be interpreted that participants learned to anticipate the motor sequence and the following ink of the word. Therefore, participants became better at handling

Stroop conflict at the end of the training. Above that, the results also imply that cognitive control is higher, when participants are familiar with the motor sequence. Yet, it was shown that, when they were confronted with new, unfamiliar sequences of color, the Stroop conflict returned to its starting level. The analysis of the participants' awareness of the underlying sequences showed that explicit knowledge about the underlying sequence is not responsible for the effect of motor learning on cognitive control. The results lead to the conclusion that motor learning processes could be used to avoid Stroop conflict and thus support the inhibition of automatic responses, meaning cognitive control.

The results of this study support the Dual Processor Model of sequential motor learning (Abrahamse et al., 2013; Verwey, 2003). It is likely that participants have acquired sequential motor skill as described in the DPM. Presumably, in the beginning of the experiment, they were heavily relying on the cognitive processor to translate every stimulus into the respective response (reaction mode). After executing the series of movements repeatedly, only the first stimulus is needed to trigger the entire sequence (chunking mode). In the end, a series of different movements were integrated in one single memory representation (motor chunks), leading to open-loop control. It is likely that this decrease of cognitive load in the cognitive processor enables to anticipate the upcoming events on the basis of the previous events rather than focusing on each event separately. Ultimately, this allows responding to a series of stimuli in a reflexive manner. Interestingly, the DPM claims that explicit knowledge is not necessarily needed for the creation of motor chunks which might explain why there is no relation between whether participants being aware of the sequences and the decrease of cognitive conflict. In the end, substantial structural knowledge of a sequence is not of fundamental importance for the DSP task or the development of motor chunks.

In addition the findings are in line with earlier studies regarding sequential learning processes and cognitive control. Tabau and López-Moliner (2004) and Koch (2007) found that explicit sequential learning leads to cognitive conflict reduction. Tubau and López-Moliner reported that the awareness of an underlying motor sequence lead to a smaller Simon-like conflict. Koch also found that motor sequence learning allowed participants to complete the Simon task with less cognitive conflict. These results are extended by the results of this study that indicate that participants show similar results learning discrete motor sequences. The results of this study are also in line with Deroost's (2012) findings over the relationship between perceptual sequential learning on cognitive conflict reduction. In particular, Deroost found that automatisms protect against Stroop effect. In this study, these effects could also be found for automatic sequential motor learning. Whether participants learned the sequence implicitly or due to explicit knowledge of the underlying sequence through repetitive practice is still open to debate. The main issue with the Discrete Sequence Production task is that participants become aware of the sequence during practice making it not purely implicit. However, the results do not show a relationship between sequence awareness and cognitive conflict, so the debate is of minor relevance for the findings of this study.

Given the ongoing debate about whether the DSP task resembles implicit or explicit learning, it would be of interest to use another motor learning task in order to investigate the effect of implicit motor learning on cognitive control in future research. For instance, the Serial Reaction Time (SRT) task is regarded as an implicit motor learning task (Abrahamse et al., 2013; Purves et al., 2008). In it, participants perform a fixed sequence of stimulus-response events, without being explicitly informed about the underlying sequence. Increases in performance reveal that participants pick up the sequence, without being aware of it. However, in the SRT task, participants do not execute discrete movements. That means, that the generalizability of findings of research with the SRT to discrete sequential motor learning is limited.

For further future research, it would be of interest to investigate if the findings of this study could be generalized to other tasks that deal with cognitive conflict, such as the Simon task or the Eriksen Flanker task. Tubau and López-Moliner (2004) already found that explicit sequential learning decreases Simon-like cognitive conflict. In a similar manner, future research could make use of the Simon task and combine it with the DSP task. Possibilities to alternate the Simon task in order to integrate it in the DSP are changing the possible locations where a stimulus might be presented (left or right). These could be changed to four possibilities to pick from (i.e., upper/under left corner and upper/under right corner). The respective keys to respond could then be in a quadrangular fashion as well (i.e., the keys f, v, b, and h could be used). As is in this study, participants would still have to respond to the color of a stimulus. This would be of interest, not only for the purpose of generalization, but also because research indicates that Stroop conflict decreases faster than and differently from Simon-like conflict (Deroost et al., 2012).

It was found that sequential motor learning improves cognitive control. Future research could focus on the reverse direction: the effect of cognitive control on sequential motor learning. The question then would be if cognitive conflict could improve sequential motor learning. Findings in the study of Deroost et al. (2012) indicate that the higher the cognitive conflict the higher the perceptual sequential learning. In a similar manner this could also account for motor learning. In order to investigate impact of cognitive conflict, the degree of cognitive conflict within a Stroop task could be manipulated. For instance, one could use a high conflict (i.e., 50 – 50), a medium conflict (i.e., 75 – 25), and a no conflict (i.e., neutral words instead of color words) group and investigate which group shows the greatest improvement in motor learning. In line with the study Deroost et al. (2012) it would be expected that the higher (i.e., 50 – 50) cognitive conflict the greater the improvement of sequential motor learning.

Moreover, what cannot be concluded on the basis of the results is that cognitive conflict could be overcome completely by sequential motor learning. Nevertheless, the findings display a steady decrease of conflict over practice, which might indicate the Stroop conflict would diminish completely if the practice phase was extended. This assumption is supported by findings of Deroost et al. (2012) which indicate that cognitive conflict disappeared as a result of perceptual sequence learning but needs to be investigated further in future research.

The study had certain limitations, which can be prevented in future studies. First of all, the sample consisted of students from the University of Twente. During their education, all of them have to complete several basic psychological paradigms, one of them being the Stroop task. Further, some of the students already had experience with the DSP task or with other sequential tasks. Secondly, some flaws in the procedure became obvious. After finishing each block, participants were asked to call in the researcher to start the next block manually. Some participants reported that it would be better if they would not see what the researcher was doing because for the practice phase the same file was opened and participants became suspicious and began looking for similarities among the different blocks. Thirdly, participants reported difficulties distinguishing green and yellow on the provided paper since they were next to each other and on the computer screen. For future research, it can be recommended to separate green and yellow further by at least one key and to increase the contrast of the monitor.

In summary, it was in this study that Stroop effect decreased over practicing an underlying sequence. Further, the results indicated that Stroop effect recovered fully when participants were confronted with unfamiliar sequences that they had not practiced before. The results can be explained in terms of the Dual Processing Model of sequential motor learning. Future research could focus on generalizing these findings to other cognitive conflict situations and investigate if cognitive conflict not only decreases but also disappears completely after repeated execution of motor sequences. Another possibility would be focusing on the effect of cognitive conflict on sequential motor learning. Taken together, this study showed that motor learning processes can contribute to cognitive control processes.

References

Abrahamse, E. L., Ruitenberg, M. F. L., De Kleine, E., & Verwey, W. B. (2013). Control of automated behavior: Insights from the Discrete Sequence Production task. *Frontiers in Human Neuroscience, 7*. doi:10.3389/fnhum.2013.00082

Annett, M. (1970). A classification of hand preference by association analysis. *British Journal of Psychology, 61*, 303-321.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 624–652. doi:10.1037/0033-295X.108.3.624

Deroost, N., Vandenbossche, J., Zeischka, P., & Soetens, E. (2012). Cognitive control: A role for implicit learning? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*, 1243–1258. doi:10.1037/a0027633

Koch, I. (2007). Anticipatory response control in motor sequence learning: Evidence from stimulus–response compatibility. *Human Movement Science, 26*, 257–274. doi:10.1016/j.humov.2007.01.004

Tubau, E., & López-Moliner, J. (2004). Spatial interference and response control in sequence learning: The role of explicit knowledge. *Psychological Research, 68*, 55–63. doi:10.1007/s00426-003-0139-4

Purves, D., Brannon, E. M., Cabeza, R., Huettel, S. A., LaBar, K.S., Platt, M.L.,& Woldorff, M.G. (2008). *Principles of Cognitive Neuroscience*. Sunderland, Massachusetts U.S.A.: Sinauer Associates, Inc

Ruitenberg, M. F. L., Abrahamse, E. L., & Verwey, W. B. (2013). Sequential motor skill in preadolescent children: The development of automaticity. *Journal of Experimental Child Psychology, 115*, 607–23. doi:10.1016/j.jecp.2013.04.005

Ruitenberg, M. F. L., De Kleine, E., Van der Lubbe, R. H. J., Verwey, W. B., & Abrahamse, E. L. (2012). Context-dependent motor skill and the role of practice. *Psychological Research, 76, 812–820*. doi:10.1007/s00426-011-0388-6

Verwey, W. B. (2003). Processing modes and parallel processors in producing familiar keying sequences. *Psychological Research, 67*, 106–122.

Verwey, W. B. (2010). Diminished motor skill development in elderly: indications for limited motor chunk use. *Acta Psychologica, 134*, 206–214. doi:10.1016/j.actpsy.2010.02.001

Verwey, W. B., Abrahamse, E. L., Ruitenberg, M. F. L., Jiménez, L., & De Kleine, E. (2011). Motor skill learning in the middle-aged: Limited development of motor chunks and explicit sequence knowledge. *Psychological Research, 75*, 406–422. doi:10.1007/s00426-011-0320-0

Verwey, W. B., & Wright, D. L. (2004). Effector-independent and effector-dependent learning in the discrete sequence production task. *Psychological Research, 68*, 64–70. doi:10.1007/s00426-003-0144-7