Is learning movement sequences influenced by eye fixation location?

Bachelor Thesis

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Abstract

In order to better understand if changing gaze location has an influence on motor sequence learning, 24 participants were tested doing a discrete sequence production (DSP) task. The aim of the study was to find out if participants develop a retinotopic sequence representation during the execution of the DSP task. High and Low practice groups practiced the two sequences while gazing at an X located at either the left or the right side of the screen. During the test phase, the participants changed fixation location and sequences in order to test whether the reaction time changed in the execution of the task. The experimental results showed that only participants who had extended practice and were performing familiar sequences had an increased reaction time when changing the gaze to an unfamiliar location. This effect is explained by the development of retinotopic sequence representation. The retinotopic sequence representation was developed only for the participants that had an extended practice and that therefore, already developed a sequence representation.

Introduction

Most of everyday activities, such as walking or typing on the computer, require movements. Motor skills can be acquired by learning skills processes which change internal cognitive processes through practice and experience that results in the ability to respond and/or produce motor skills (Seidler, Bo, & Anguera, 2012). Automatic motor skills develop via cognitive processes which change motor memory. Motor memory can be defined as containing the representations of motor actions that are acquired through practice and experience (Kantak, & Winstein, 2012). Once the information is learned, it is stored temporarily in working memory which allows manipulation of that information (Seidler, Bo, & Anguera, 2012). According to Bo and Seidler (2009), visuo-spatial working memory has a direct link to explicit motor sequence learning. The visuo-spatial working memory is a cognitive system that involves active storage of information and processing to shape information of a task which creates explicit motor learning characterised by the ability to verbalize what has been learned (Bo, & Seidler, 2009).

One method to explore sequence learning is through the use of the discrete sequence production (DSP) task. The DSP task requires the participant to type sequences of keys corresponding to what they see on the screen in order to learn those sequences (Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013). Typically, the sequences include 6 successive stimuli (Verwey, Shea, & Wright, 2015). During the sequences, the reaction time (RT) and accuracy are measured.

The present experiment is based on the experiment previously carried out by Rödig (2009). Rödig's (2009) experiment investigated how frame of reference changed in motor sequence learning. The experiment was carried out using the DSP task and participants were instructed to focus on a Fixation cross (X) located at the right or left gaze of the screen and to subsequently adjust their gaze during the task to the unfamiliar gaze. The change of frame of reference increased the RTs of participants when executing the practiced sequence.

The present experiment was conducted to test if the reduction in the execution rate was caused by the development of a retinotopic sequence representation or due to the change of frame of reference per se during the sequence execution of the DSP task. A retinotopic sequence representation is a representation of the order of the stimuli in terms of visuospatial coordinates relative to their projection on the retina. For this experiment, the cognitive framework for sequential motor behaviour (C-SMB) was used to identify sequence execution of participants by using central-symbolic and motor representations (Verwey, Shea, & Wright, 2015). The C-SMB framework assumes that various types of representations are involved in motor skill learning. This would underlie sequential behaviour at three processing levels: perceptual, motor, and central. Central-symbolic representations are sequence representations used at the central processing level, but which are not related to perceptual and motor processing levels. Central-symbolic representations are based on a low-level perceptual representation and/or a motor representation (Verwey, Shea, & Wright, 2015).

Motor chunks are used in motor sequence learning and are created by breaking down large sequences of movement into smaller ones in order to memorize information (Sakai, Kitaguchi, & Hikosaka, 2003). Moreover, motor chunks occur at the motor processing level which require cognitive processing. Cognitive processing is necessary in order to initiate and select sequences, subsequently motor chunks are executed autonomously (Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013). According to Anderson (1982), when a person learns a sequence they go through several steps ranging from the initial attention phase to the automatic phase, which allows them to perform the action without paying attention .

Verwey, Shea, and Wright (2015) proposed several assumptions regarding sequential motor behaviour. One of these assumptions is that short-term storage of information involves two stores, short-term memory and the motor buffer. The motor buffer stores motor representations that consist of movement features and information to perform the actual movement. What's more, a motor buffer has a capacity of only 3 to 5 elements meaning that longer sequences need motor representations (Verwey, Abrahamse, & Jiménez, 2009). Motor representations can be transferred from long-term memory to the motor buffer by activating a few of the features in that representation (Verwey, Shea, & Wright, 2015).

Chunking

As previously explained motor chunks are representations of simple movements which, in order to learn a motor skill, are stored in long-term memory. A peculiarity of these motor chunks is that they can be selected and performed as if they were single responses in a sequence of movements (Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013). Motor chunks are used for movements the same way as memory chunks are used for facts. When learning a motor skill, motor chunks are combined and used in order to execute a certain movement. (Seidler, Bo, & Anguera, 2012). Additionally, the performance of a motor skill involves representations that contain 3 to 5 elements (i.e., responses). These elements together form central-symbolic representations that, with practice, create motor chunks in long term memory (Verwey, Shea, & Wright, 2015).

Frame of reference

Motor sequences are represented by a spatial code in the initial learning stage, such as central-symbolic representations, therefore, the frame of reference is an important construct to understand motor sequence learning (Verwey, Shea, & Wright, 2015). Frame of reference can be defined as the perception and encoding of the surrounding space of an object with respect to a reference point. Motor learning occurs at an allocentric and egocentric frame of reference during sequence learning. The allocentric frame of reference refers to a point of reference located outside the body, for example, an object or a cardinal point. By contrast, the egocentric frame of reference refers to a point relative to the body such as one's arm or one's head (Witt, Ashe & Willingham, 2008). For motor sequence learning, occurring as a collection of finger movements, an egocentric frame of reference is used (Liu, Lungu, Waechter, Willingham, & Ashe, 2007). However, different egocentric frames of reference can be used in order to execute movements, such as a hand-centred, eye-centred or retinotopic frame of reference, which are effector independent (Witt, Ashe & Willingham, 2008). According to Hikosaka, Nakamura, Sakai, and Nakahara (2002), visuo-spatial representation develops during later stages of motor sequence learning. The learner that practices motor sequences subsequently develops motor chunks which are effector-specific representations.

Retinotopic sequence representation

In Rödig’s (2009) experiment, it was suggested that participants, when learning a DSP sequencing task, develop both a retinotopic visuo-spatial and motor chunk representations of the sequence. With the present experiment, we tested if there indeed was a retinotopic sequence representation that reduces the reaction time during the DSP task. In the previous experiment, participants gazed at a fixed location at the right of the display while stimuli, necessary for the keying sequences, were displayed in the centre. Evidence for the retinotopic representation was that gazing at another location than during practice reduced the execution rate. This occurred in groups practicing for both 50 and for 450 trials per sequence. This suggests that this retinotopic representation develops quite rapidly. Additionally, the 450-practice trial group showed slowing when they used different fingers than during practice, but the 50-trial group did not. This indicated that effector-specific sequence learning occurred after 450, but not after 50 practice trials per sequence, meaning that participants developed motor chunks.

It is possible that in Rödig's (2009) experiment, participants learned to fixate at a particular location and learned to extract information from one specific part of their visual field rather than developing some kind of retinotopic sequence representation. When they attended to the unfamiliar gaze location this required more processing resources because it required learning to fixate at another location, and it may have been that this reduced execution rate. So, the slowing may have been caused by learning to attend to the unfamiliar fixation point rather than by developing a retinotopic representation of the stimuli. The goal of this experiment is to test which of these alternatives is the proper one, learning to attend to the unfamiliar fixation point and extract information from a specific part of the visual periphery versus the development of a retinotopic sequence representation.

Present experiment

Based on Rödig's (2009) study, the following experiment is aimed at investigating if the increased reaction time of participants while gazing at the unfamiliar fixation location was due to the development of a retinotopic sequence representation or due to having to look at the unfamiliar fixation point while executing the sequence. In the present experiment, participants were divided into two groups. The first group was a low practice group where participants had 50 trials in the practice phase. The second group was a high practice group where participants had 450 trials in the practice phase.

Because the aim of this experiment was to test if a retinotopic sequence representation develops during practice, both groups were gazing at a fixation cross located at the left or right side of the monitor while the key-specific stimuli were displayed around the centre. The gaze location during the practice phase was not changed. The fixation cross location was subsequently changed in the test phase for both groups. Both groups practiced with a set of key sequences (6 keys) using the same hand and fingers for both the practice and the test phase. Participants practiced two sets of sequences of keys during practice and subsequently they executed two unfamiliar sequences during the test phase. The relevance of changing sequences from familiar to unfamiliar in the test phase is to verify whether sequence representation develops with practice. Based on previous studies, this experiment explores whether there is a retinotopic sequence representation that decreases the reaction time during the execution of the DSP task when sequence production is changed. According to Rödig's (2009) experiment, it is predicted that when the fixation cross is located at the side of the display that was not practiced with for both groups (High and Low practice), the reaction time decreases. However, for the present experiment, the change of sequence in the test phase is carried out for both practice groups to test if the frame of reference manifests itself.

Hence, the hypothesis was that there is a retinotopic sequence representation in the high practice group for the practice sequence. It was predicted that the extended practice group's reaction time increases when gazing at the familiar fixation point location while executing the same sequence practiced in the practice phase. This effect is due to the development of a retinotopic sequence representation based on the familiar fixation point location. The development of a sequence representation is expected for both practice groups as it was also reported from Rödig (2009). Additionally, it is predicted that the change of frame of reference from practice to test phase decreases the RTs of participants in both practice groups when executing the familiar sequence.

Methods

Participants

A total of 24 participants took part in the experiment, 15 female and 9 male, aged between 18 and 29 (M_{age} ~21). The participants were split into 2 groups, 12 participants in the high practice group and 12 participants in the low practice group. All participants were students at the University of Twente, right-handed and did not have a visual or motor impairment. Participants did not consume alcohol in the previous 24 hours and were not heavy smokers. Additionally, all the participants were checked for colour-blindness prior to the experiment and none of the participants appeared to be colour-blind. The research has been approved by the ethical committee of the faculty of Behavioural, Management, and Social Sciences (BMS) of the University of Twente. Before the experimentation, every participant had to sign an informed consent and a Covid-19 regulation form.

Apparatus

The experiment was conducted at the BMS lab of the University of Twente in a Flexperiment cubicle. The room was equipped with a computer with Windows 10 and a monitor working at a 144 Hz refresh rate. A PS/2 QWERTY keyboard was used to press keys during the DSP task. A chin rest was positioned 50 cm in front of the monitor in a central position and the keyboard was located in between the monitor and chinrest. Additionally, Tobii pro 2 eye-tracking glasses were used to control and record the fixation point of the participants on the monitor screen. The X's luminance was measured for both sides of the monitor screen. The right side had a red luminance of 78 lm and green luminance of 77 lm, the left side had a red luminance of 75 lm and a green luminance of 64 lm.

Task

The participants completed the discrete production (DSP) task using the index finger of one hand and the middle and index finger of the other hand. For the experiment, there were 2 different configurations: 2L1R (index and middle finger of the left hand and index of the right hand) and 1L2R (index of the left hand and index and middle finger of the right hand). The DSP task involved three square placeholders on a light grey background, the squares corresponded to the "F", "G", and "H" keys on the keyboard. The squares of the DSP task were 2 by 2 cm and spaced 5 cm between each other. The X was positioned at the same height as the squares, 1 cm from the left or right monitor border and 11 cm from the squares.

The participants performed 2 sequences of 6 keys each (half of the participants had FHGHFG vs. HFGFGH and the other half had HGHFGF vs. FGFHGH). The squares lit up in green to indicate the key to be pressed. If the participant made an error, the program informed the participant and the sequence started again from the first key. For every error, the participants had to wait as a penalty for 3 seconds intended to motivate the participant to not make errors in further sequences. An error with this time penalty was also given if the participants typed too early or too late. During the experiment, the participants were told to fixate their gaze on the X at the extremity of the monitor screen and to count how many times it changed colour from green to red. At the end of every subblock (2 subblocks for every practice phase blocks and 4 subblocks for the last test phase block), the participant reported how many X's they had counted. They were then shown the correct answer with their error rate and average reaction time for that subblock. In between the subblocks of a block, there was a 20 seconds break and in between blocks there was a three-minute break.

Procedure

The experiment started after making sure the participants signed the informed consent form and adjusted the height of the chair together with the height of the chinrest. Next, the Tobii pro 2 glasses were set and calibrated. All the participants were also asked to read an Ishihara colour test in order to verify they were not colour-blind.

The participants were divided into 2 groups, High and Low practice. Each practice block had 50 trials and the X was always positioned at the same side of the screen for the entire practice phase. In total, the Low practice group practiced each sequence 50 times and the High practice group practiced each sequence 450 times. The High practice group had 9 practice blocks and the Low practice group had just 1. Participants 1 to 6 performed the experiment with the finger configuration 2L1R and located their gaze to the right side of the screen. Participants 7 to 12 performed the experiment with finger configuration 1L2R and located their gaze at the right side of the screen. Participants 13 to 18 performed the experiment with the finger configuration 2L1R and located the fixation point at the left side of the screen. Finally, participants 19 to 24 performed the experiment with the finger configuration 1L2R and located their gaze at the left side of the screen.

Block 10 for the high practice group and block 2 for the low practice group constituted the test phase of the experiment. Those blocks consisted of four subblocks during which the participants changed their fixation location and sequence production relative to the one used during practice. The subblocks' orders were counterbalanced across participants. The four subblocks had different conditions. Respectively two subblocks had the fixation point location of participants the same as the one practiced in practice phase, a familiar fixation point. However, one of these subblocks had a different sequence from the practice phase and the other had the same sequence. On the contrary, the other two subblocks involved an unfamiliar fixation point, different from the practice phase. Correspondingly, one of these subblocks had a different sequence from the practice phase and the other had the same sequence.

At the end of the experiment, participants were asked to fill out an awareness test and recall the sequences they had been practicing and subsequently had been tested on. The order of the verbal and spatial test analysed in the awareness test were counterbalanced across participants. On the one hand, the verbal test consisted in participants recalling the sequences by clicking squares that were shown on the display with the mouse, representing the 3 sequence keys (“F” “G” “H”) used in the experiment. The position of the squares was scattered to make the participants recall the sequence letters. On the other hand, the spatial test consisted in participants recalling the sequences by clicking unmarked squares positioned in the familiar experimental position. At the end of both spatial and verbal tests, participants were asked how sure they were about their answers.

Data Analysis

Repeated measure analyses of variance (ANOVA) were used to analyse the reaction time and the arcsine-transformed error rates for the practice and test phase. Greenhouse-Geisser transformation was used when the sphericity assumption was violated.

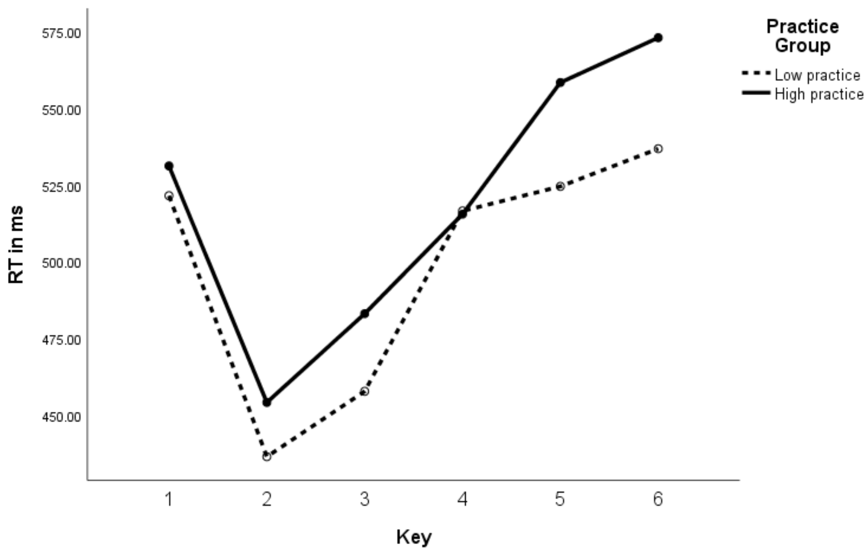
Results

Practice Phase

The first analysis involved practice block 1 and was carried out to investigate potential between-group differences (Figure 1). The analysis involved a 2 (Practice Group; High and Low practice) x 2 (Fixation Point; Left and Right) x 6 (Keys) ANOVA with Fixation Point and Practice group as between-subject variables and Key as within-subject variables. The two practice groups did not show significant differences in the first practice block, $F(1,20) = 0.30$, $p = .59$. Furthermore, the ANOVA showed a different reaction time depending on the Key pressed during the first practice block, $F(2.6,51.6) = 8.5$, $p < 001$, $\eta_p^2 = .29$ (Figure 1).

Using the arcsine-transformed error rates the insignificant difference between subjects of the practice groups was confirmed, $F(1,20) = 0.71$, $p = .41$. Additionally, both groups also had a different error rate depending on the key they were pressing, $F(3.97,79.42) = 7.03$, $p < 001$, $\eta_p^2 = .26$.

Figure 1.
Reaction times of both practice groups for the individual key presses in Block 1



In order to analyse the RTs of the high practice group a 2 (Fixation Point; Left and Right) x 9 (Blocks) x 6 (Keys) design was used. The fixation point was a between-subject variable and Block and Keys were within-subject variables. The ANOVA showed that there was a significant effect of Block, $F(3.1,30.6)=63.83$, $p<.001$, $\eta_p^2=.86$ (Figure 2) and Keys, $F(2.5,25.3)=18.30$, $p<.001$, $\eta_p^2=.647$ on RT. Additionally, the findings showed that the high practice group had a significant Block by Fixation Point interaction, $F(3.06,30.62)=4.787$, $p=.007$, $\eta_p^2=.32$, meaning that fixation location had a smaller effect in Block 9 (247 ms) than in Block 1 (509 ms). Moreover, a Block by Key interaction, $F(4.52,45.22)=11.767$, $p<.001$, $\eta_p^2=.541$, indicating that the RT in Block differs per key press.

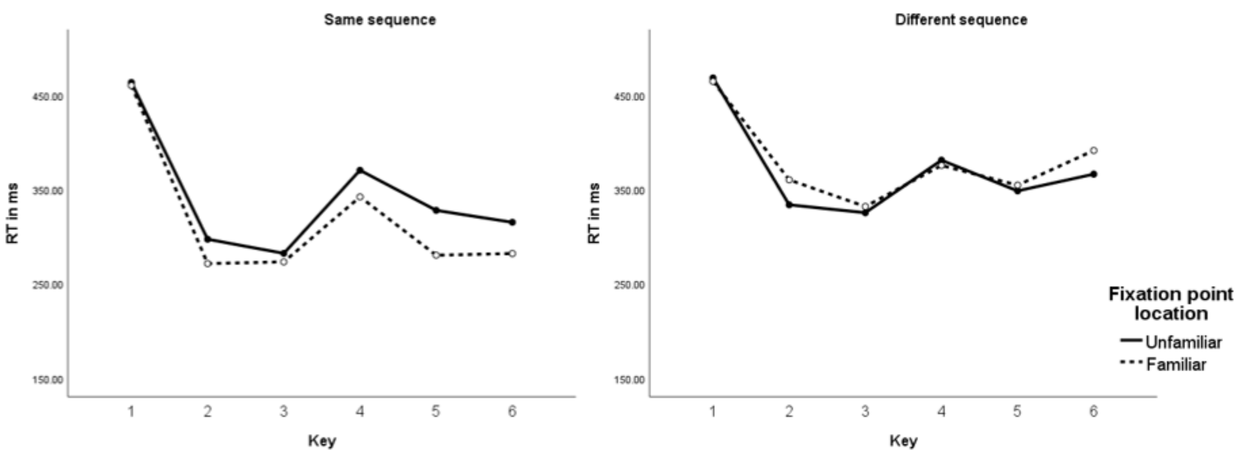
Using the same design for the high practice group, the arcsine-transformed error proportions were analysed. The error rate analysis showed that participants had a different error rate depending on the Block they were executing, $F(3.46, 34.58)=2.91$, $p=.042$, $\eta_p^2=.22$, and the Key they were pressing, $F(2.56,25.63)=13.04$, $p<.001$, $\eta_p^2=.566$. These results showed that participants had a lower error rate in Block 9 than in Block 1, and participants had a higher error rate for the fourth key (4.8% error rate) of the sequence in comparison to the other keys (respectively, Key1 =2.4%, Key2 =2.4%, Key3 =2.8%, Key5 =2.9% and Key6 =2.4%). Moreover, the findings showed that the variable Fixation point had a significant effect on the error rate of participants, $F(1,10)=5.576$, $p=.04$, $\eta_p^2= .36$. When participants were gazing at the left side of the screen they had a higher error rate in comparison to participants who were gazing at the right side of the screen (respectively, LX=3.2% and RX=1.5%).

Test phase

The RTs in the test phase were analysed using a 2 (Practice Group; High vs Low practice) x 2 (Fixation Point: unfamiliar vs. familiar position from the practice phase) x 2 (Sequences: different vs. same as in the practice phase) x 6 (Key) design. The independent variable Practice Group was a between-subject variable and Key, Sequence, and Fixation point were within-subject variables. The ANOVA showed that the RTs were shorter for the High practice group than for the Low practice group (285ms vs. 421ms, respectively), $F(1,22)=13.51$,

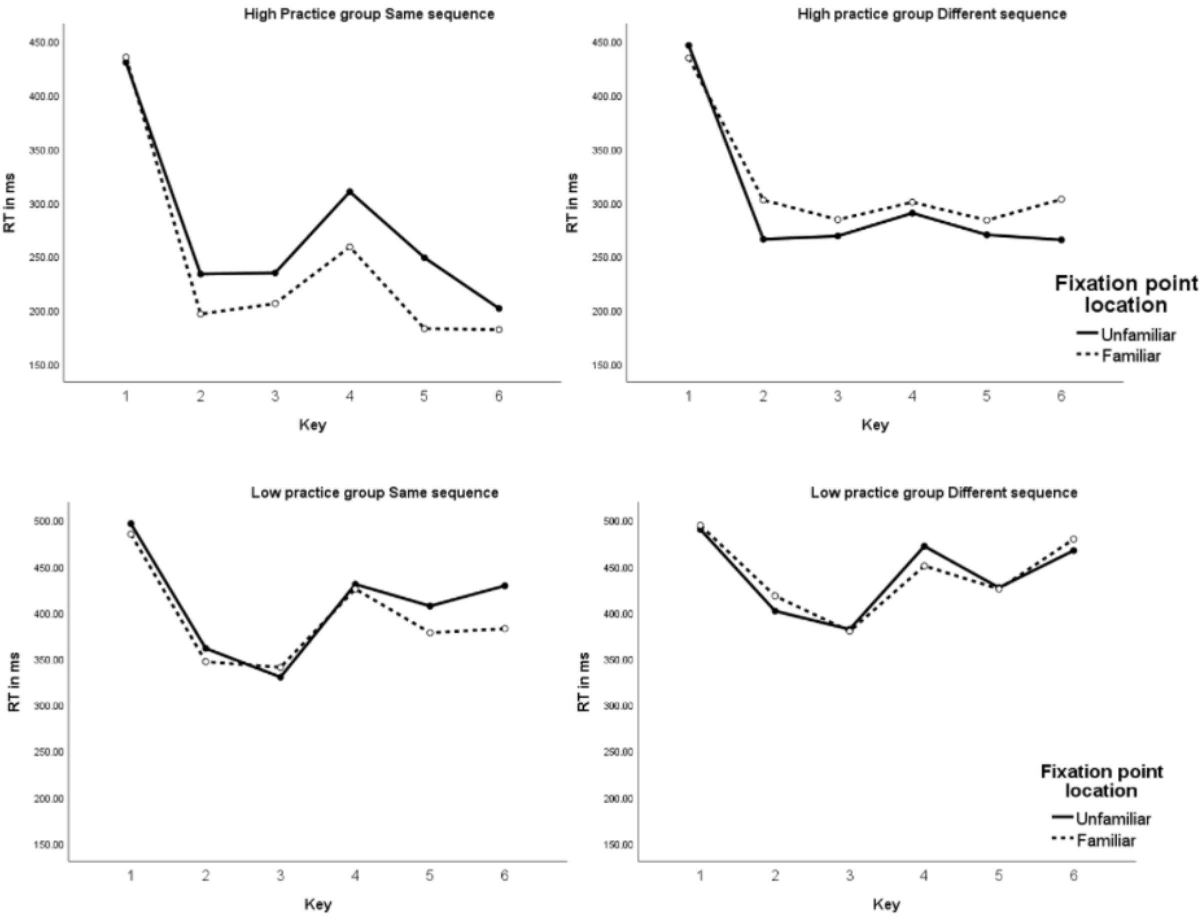
$p=.001$, $\eta_p^2=.38$. Moreover, the findings showed that participants' RTs were different depending on the Key they were pressing, $F(3.05,67.04)=23.95$, $p<001$, $\eta_p^2=.52$. Accordingly, the fourth key had a longer RT than the other keys. Additionally, the RTs of participants when executing the unfamiliar sequence was longer than when participants were executing the familiar sequence, $F(1,22)=4.57$, $p=.044$, $\eta_p^2=.172$ (respectively, 375 ms vs. 321 ms). Additionally, the ANOVA showed that there is an interaction between the Practice Group and Key pressed, $F(3.05, 77,04)=4.412$, $p=.007$, $\eta_p^2=.167$. A significant interaction was also found between Key and Sequences ($F(2.79,61.38)=4.206$, $p=.011$, $\eta_p^2=.16$) meaning that the effect of familiar or unfamiliar sequences is different per key. Furthermore, a significant interaction was found between the variables Key, Fixation Point, and Sequences $F(3.67,80.82)=3.339$, $p=.016$, $\eta_p^2=.13$ (Figure 2).

Figure 2.
Interaction between Fixation location, Key production, and Sequence familiarity.



Importantly, the ANOVA revealed an interaction between the Fixation point, Key, Sequence and Practice group, $F(5,110)=2.39$, $p=.043$, $\eta_p^2=.098$. This final significance showed that the effect of the Fixation point, Key, and Sequence tend to be greater for the high practice group rather than the low practice group (Figure 3).

Figure 3.
Interaction between Fixation location, Key production, and Sequence familiarity in High and Low practice groups.



Following the same analysis as before, the error rate with arcsine-transformation results demonstrated that there was no difference between the error rates of practice groups, F(1,22)=3.52, p=.074. By contrast, depending on the key pressed the error rate changed for participants in both practice groups, F(3.92,86.20)=7.075, p<.001, η_p^2=.243. Key also interacted with Fixation point, F(3.98,87.46)=2.728, p=.03, η_p^2=.1, meaning that unfamiliar fixation location increased the keypress error rate of participants.

Discussion

The purpose of this study was to explore whether during the sequence learning process participants develop a retinotopic sequence representation. A DSP task was used to determine participant's reaction to gaze location unfamiliarity and familiarity depending on the amount of experience they had practicing sequences. This experiment aims to comprehend if the reduction in participants' RT during DSP task found in Rödig's (2009) experiment is due to the development of a retinotopic sequence representation or due to participants learning to attend to a particular part of their visual field. The present experiment was based on Rödig's (2009) study that found a significantly increased RT when participants in both practice groups changed to an unfamiliar fixation point location from the one they were practicing.

The present experiment hypothesized that participants who had an extended practice on a familiar fixation point with the same sequence would have an increased reaction time when the frame of reference is changed to an unfamiliar location. This effect was predicted to occur as a result of the development of a retinotopic sequence representation based on the familiar fixation location. Rödig's (2009) study showed that participants in both practice groups developed a sequence representation, this was the case also in the present experiment. Nonetheless, the findings of the present experiment showed that only participants who had extensive practice executing the familiar sequence had an increased RT when the frame of reference was changed to the unfamiliar location. However, the unfamiliarity with the fixation point location did not have any reduction effect on the RT when the sequence was unfamiliar. Moreover, the increased reaction time did not occur for the group with short practice neither when the sequence production was familiar nor unfamiliar.

With this in mind, it may be argued that the longer RTs with the unfamiliar frame of reference shown by Rödig's (2009) experiment is not exclusively due to the fixation location. On the contrary, the increased RT seems to be affected also by the participants' amount of knowledge of the sequences. Accordingly, sequence representation developed based on the retinotopic sequence representation on the familiar fixation location. Thus, it can be assumed that maintaining the familiar fixation point location keeps visuospatial attention on task-relevant stimuli (Rosenthal, Mallik, Caballero-Gaudes, Sereno, & Soto, 2018). The task relevant stimulus in the present experiment using DSP task would be the familiar fixation point which has developed into retinotopic sequence representation with extended practice. Participants learned the sequence creating sequence representation and when they had to change their frame of reference to an unfamiliar location, their reaction time increased. Therefore, a retinotopic sequence representation developed for the practice sequence in the High practice group which would seem to confirm the hypothesis.

According to Hikosaka et al. 's (1999) model, the motor component in the late learning stage is heavily active, meaning that participants would be able to change their frame of reference without changing their reaction time. This phenomenon would be explained by the active motor component that participants develop in the late learning process. In the present experiment it was shown that the relocation of the fixation point had an effect on the motor skill learning process. Additionally it was also found that the change in sequence production also had a major impact on the results, indicating that the motor component is active, confirming the findings by Hikosaka et al. (1999). The strong effect of sequence might be explained by Verwey, Shea, & Wright, (2015) framework in which sequences are represented at multiple levels, indicating that multiple multi-level sequence representations are active at the same time.

Furthermore, participants had learned the sequences by dividing them into chunks independently from which practice group they were located in. The results showed that the participants had an increase in reaction time when performing the fourth key, meaning that participants split the chunking into two separate motor chunks. These findings coincide with the results found by Verwey (1996) explaining that people preserve the sequence they have been practicing and chunking, even if doing so is not advantageous for their memory.

Limitations

The results might have been influenced by the equipment used during the experiment. The Tobii 2 pro eye-tracking glasses were used in order to verify that the participants were fixating at the X during the experiment. However, the eye-tracking glasses have a slightly darker lens tone that might have influenced the participants' colour vision. Even though the luminance of the computer display was calculated and calibrated, it was not calibrated together with the Tobii pro 2 glasses lens tone. It is believed, that the lens tone did not influence the result of this experiment, but in order to have more accurate results it would be advisable to correct the luminance problem in future research or to check the participants' colour vision with the use of the eye-tracking glasses.

Another limitation reported during the experiment is the difficulty for some participants on using the three sequence keys ("F" "G" "H"). According to participants' experiences the keys were too close to each other making it difficult to type sequences on the keyboard. Despite the problem, it is assumed that this limitation did not have a significant effect on the results. For future studies it is advisable to use more distant sequence keys or a bigger keyboard in order to reduce the possible error rate derived from this limitation.

Conclusion

In conclusion, this paper was aimed at testing whether during motor sequence learning, learners develop a retinotopic sequence representation with practice. This experiment expands the results found by Rödig's (2009) study by explaining that the reduction in RT during the DSP task is not due to the change in the frame of reference as reported by Rödig's (2009).

The hypothesis for this experiment was that a retinotopic sequence representation would develop in the extended practice group for the practice sequence. Contrarily from Rödig's (2009) study that has found an increased RT for both practice groups, the hypothesis for the present experiment was that the change in the fixation point location would affect only participants who had an extensive practice of the sequence. Indeed, the hypothesis was confirmed by the increased reaction time in participants that had an extended practice and the fixation point was changed. Only when the sequence production was an automatic process the retinotopic sequence representation could develop. Therefore, the slowing in RT found by Rödig (2009) is not due solely to the change in the fixation point location considering that this variable did not have an influence when participants had to perform an unfamiliar sequence. Future research should investigate when exactly learners develop a retinotopic sequence representation and possibly try to validate the results made in this experiment.

References

Abrahamse, E., Ruitenberg, M., De Kleine, E., & Verwey, W. B. (2013). Control of automated behavior: insights from the discrete sequence production task. *Frontiers in human neuroscience*, 7, 82.

Anderson, JR (1982). Acquisition of cognitive skill. *Psychological Review*, 89 (4), 369.

Bo J. and Seidler R. D. (2009). Visuospatial Working Memory Capacity Predicts the Organization of Acquired Explicit Motor Sequences. *Journal of Neurophysiology,* 101 (6) 3116-3125

Hikosaka, O., Nakamura, K., Sakai, K., & Nakahara, H. (2002). Central mechanisms of motor skill learning. *Current opinion in neurobiology*, 12(2), 217-222.

Hikosaka, O., Sakai, K., Lu, X., Nakahara, H., Rand, M.K., Nakamura, K. Miyachi, S., & Doya, K. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences*, 22 (10), 464-471.

Kantak, SS, & Winstein, CJ (2012). Learning – performance distinction and memory processes for motor skills: A focused review and perspective. *Behavioral brain research*, 228(1), 219-231.

Liu, T., Lungu, O.V., Waechter, T., Willingham, D.T., & Ashe, J. (2007). Frames of reference during implicit and explicit learning. *Experimental Brain Research*, 180 (2), 273-280.

Rödig, V. (2009) Effects of frames of references on the spatial and motor component in the early and late learning stages of procedural learning. (Unpublished Bachelor's thesis). University of Twente, Netherlands.

Rosenthal, C. R., Mallik, I., Caballero-Gaudes, C., Sereno, M. I., & Soto, D. (2018). Learning of goal-relevant and-irrelevant complex visual sequences in human V1. *Neuroimage*, *179*, 215-224.

Seidler, RD, Bo, J., & Anguera, JA (2012). Neurocognitive contributions to motor skill learning: the role of working memory. *Journal of motor behavior*, 44 (6), 445-453.

Sakai, K., Kitaguchi, K., & Hikosaka, O. (2003). Chunking during human visuomotor sequence learning. *Experimental Brain Research*, 152 (2), 229-242.

Witt, J.K., Ashe, J. & Willingham, D.T. (2008) An egocentric frame of reference in implicit motor sequence learning. *Psychological Research,* 72, 542–552.

Verwey, W.B. (1996). Buffer Loading and Chunking in Sequential Keypressing. *Journal of Experimental Psychology: Human Perception and Performance*, 22 (3), 544-562.

Verwey, W. B., Abrahamse, E. L., & Jiménez, L. (2009). Segmentation of short keying sequences does not spontaneously transfer to other sequences. *Human Movement Science*, 28(3), 348–361.

Verwey, W. B., Shea, C. H., & Wright, D. L. (2015). A cognitive framework for explaining serial processing and sequence execution strategies. *Psychonomic bulletin & review*, 22(1), 54-77.