Investigating Motor Learning Processes: The Role of Spatial Representations, Hand Postures and their Transfer

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Abstract

This chording-study tested the hypothesis that a spatial representation facilitates chord skill after practice and that it can be mirrored within one hand. Furthermore, the hypothesis that either a spatial or hand posture representation facilitates chord skill after practice and can be transferred to the other hand of the mirror sequence was tested. For this purpose, 12 participants practiced two bimanual four key chords. Each chord was practiced for 560 trials across seven blocks. Then, the performance of participants on versions of the chords mirrored across and within the hand as well as practiced and novel chords was tested in the final block. Performance measures were Reaction time (RT) and Error proportion. The results suggested that there is no spatial representation that facilitates chord skill and that there is no transfer of a spatial or hand posture representation to the other hand of the mirror sequence. The findings of this study are somewhat limited by statistical power and balancing constraints, further research might be needed to give more conclusive answers.

Keywords: chord learning, spatial representation, hand postures, transfer

Introduction

The movement of our limbs is something that most of us do not put a lot of thought into. Nevertheless, most people have several skills, such as playing musical instruments, video games, sports or crafts, that require complex motor skills. While challenging, learning these skills seems to happen automatically, through practice, without much thought being into the specifics of how the process works. However, questioning this process is a main concern in the field of motor learning research. Deepening our understanding of motor-skill acquisition is important to a variety of areas of research (Dahms et al., 2019; Wolpert et al., 2011). One example of this is helping the recovery of stroke patients. A comprehensive insight into motoric learning has immense potential to help design the best, most individualized rehabilitation strategies for patients with brain damage (Dahms et al., 2019). Furthermore, learning new motor skills, or refining existing ones, is something that is a part of everyone's daily life. Thus, understanding the underlying processes can potentially yield improvements to the ways in which we learn and adapt to our environment (Wolpert et al., 2011). Lastly, there is also some potential for research in motor control to yield progress in the field of robotics, mainly for the models used for learning and control (Wolpert et al., 2011).

There is a wide range of mechanisms involved in the learning of motor skills. These involve extracting information, motor representations, making decisions and different classes of control mechanisms (Wolpert et al., 2011). Exploring all of these mechanisms would exceed the scope of this study. Thus, this study will focus on the topic of motor representations, expanding on the research done by Verwey (2023). That study used a chord task as an example of learning complex motor skills. In a chord task, playing a musical instrument is simulated by pressing multiple keys on a computer keyboard simultaneously. The study explored in which way learned chords are represented in the brain. The two explored concepts were the motoric learning of the **hand posture** that is required to execute the chord versus the cognitive learning of the **spatial representation** of the chord (Verwey, 2023). These two concepts will be explored in the following paragraphs.

Posture learning

There is a variety of evidence that suggests that pre-stored body postures play a significant role in the execution of the body's motor function (Romano et al., 2021;Verwey, 2023; Wang et al., 2020). One study suggests that the body has a hand posture (Thumb down pinch grip) which is favored for the execution of motor tasks (Romano et al., 2021). This hand posture leads to more motor cortex excitability which is associated with several behavioral benefits. It is likely that this is due to the hand posture matching the default spatial representation of the hand used for perception (Romano et al., 2021). This means that the hand posture is similar to the way our brain imagines our hand in its normal position. This finding shows the importance of hand postures for motor tasks on the one hand but also emphasizes the interaction of spatial representations and hand postures. Furthermore, the study that the current study seeks to expand upon found that the skill of executing the chord task was mainly based on learned hand postures (Verwey, 2023). It is also likely that due to the complexity of our hands, simple actions such as pressing a button with a single finger might already require a variety of stored hand postures for their execution(Verwey, 2023). There is also some evidence that stored hand postures can be transferred between the hands. Wang et al. (2020) found that motor skill from one hand can transfer to the other hand, though they found that this effect is significantly larger for right- than left-handed individuals. This proves that the concept of motor skill transfer does exist, though it is not clear if this applies to chord learning.

Spatial Representations

Like stored body postures, spatial representations play a role in the execution of many cognitive functions, such as motoric functioning (Verwey et al., 2015). Spatial representations can be in the form of outside visual cues or internal imagery and rely on the perceptual part of the motor system. They enable cognitive simulation of motor processes and are thus crucial for a variety of learning processes (Schwartz & Heiser, 2005). In the case of the current study, the learned spatial representation of the location of the keys of each chord might be important. It has been shown in the past that reaction time increases with the number of fingers used in a chord task. This happens even after practice, which suggests some cognitive load being present, contradicting the singular relevance of hand postures (Seibel, 1963). Overall, evidence suggests that in early practice chords are represented by spatial key location and develop to being represented by a hand posture via practice (Verwey, 2023).

Non-Independence/Enslavement

When investigating how a chord task is learned, a factor that must be considered is the lack of independence of finger movement. The human hand does not support completely independent movement of individual fingers (Van Beek et al., 2018). This phenomenon has been called enslavement and may be due to various mechanical and neurological factors (Schieber & Hibbard, 1993). This is relevant to the current research, as it has been found to negatively influence performance in tasks such as typing or playing the piano (Häger-Ross & Schieber, 2000), which are very similar to the chord task. Enslavement happens primarily between the pinky, ring, and middle finger while other fingers are able to move more independently due to both mechanical and cognitive factors (Van den Noort et al., 2016). The different levels of enslavement between the fingers thus lead to different chords possessing different levels of interference from said enslavement. Overall, the extent of enslavement at play in different chord tasks has to be kept in mind, especially as it may differ between a unimanual and bimanual execution of a chord (Verwey, 2023).

Bimanual Chords

Bimanual tasks, meaning tasks using both hands, have been shown to be more complex than simply being the product of two unimanual actions (Krebs & Asfour, 2022). The previous study by Verwey (2023) found that chord execution was faster when done bimanually, likely due to lower inter-finger interference which is often caused by enslavement. This effect is explained by the Grouping Model, stating that the use of two hands utilizes a separate representation for each hand. These representations are encoded separately in the left and right cerebral hemispheres. This in turn leads to less neuromotor noise than the use of one representation with an overlap of neural areas that are located in the same hemisphere, as is the case with unimanual motor tasks (Adam & Van Gerven, 2021). Verwey (2023) also found that bimanual coordination is a skill that can be practiced, potentially enabling the simultaneous preparation of postures for both hands.

Current Study

This study sets out to answer which mechanism, spatial representations or stored hand postures, is dominant in chord learning. Furthermore, it will be explored if the learned chords can be transferred between the hands. To this end, a chord task will be utilized. In the present chord task participants practiced two bimanual chords intensively across seven practice blocks. Then, their performance was tested on the practiced and on completely novel chords as control conditions. Also, mirrored versions of chords were performed by the participants. The mirrored chords were 1-Hand Mirror Chords that were mirrored within one hand and 2-Hand Mirror

Chords that were mirrored across both hands. Performance measures were the proportion of incorrect chords and reaction times for correctly executed chords. Finding that 1-Hand Mirror Chords were performed better would show that spatial representations are an important determinant of chord learning (H1). In contrast, 2-Hand Mirror Chords performing better in the experiment would indicate that either stored hand postures or spatial representations may determine chord skill, and that they can be transferred to the other hand of the mirror sequence (H2).

H1: A spatial representation develops after chord practice, enabling the mirroring of chords within each hand

H2: A spatial or hand posture representation develops after chord practice and can be transferred to the other hand of the mirror sequence

Methods

Participants

The study used a sample of 13 participants. The majority of participants were students from the University of Twente who received 3 Sona credits in exchange for their voluntary participation. Some participants were also people from the social circles of the experimenters, participating as a favor. To participate, participants had to be between the ages of 18-35, have normal or corrected eyesight, could not be an expert in tasks such as piano playing, could not be regular smokers and have not drunk alcohol in the 24 hours prior to the experiment. One participant had to be removed from the sample due to missing data, leaving a total number of 12 participants for data analysis. This amount of participants was short of the desired sample sizes 32 or 16, where the data would have been counterbalanced regarding different combinations of fingers (Appendix 2). Of the participants, four declared their gender to be male and eight indicated identifying as female. The ages of the participants ranged from 18 to 24 (M=20.6, SD=2.18). Of the participants, 10 were right- and two left-handed. All participants agreed to the informed consent and ethical approval was given by the BMS ethics committee of the University of Twente.

Materials

The experiment was programmed in E-prime v 2.0 (Imagebox, 2023) and ran on a Dell Optiflex 7050 desktop PC. A Razor Huntsman v2 Tenkeyless optical gaming keyboard was used for the input and a 144hz Aoc Freesync monitor was used as a display. A Blackmagic camera system with a GoPro camera was utilized to check if participants had finished their trial. The informed consent (Appendix 1) was conducted using Qualtrics (Qualtrics XM - Experience Management Software, 2023). Furthermore, the questionnaire (Appendix 3) was filled out after

Block 7 with pen and paper. It recorded demographic data, tested participants' awareness during the experiment and recorded self-reported proficiency in activities that might impact performance. To test participants' awareness, they were asked to write down the key combinations that they had executed in the practice blocks. To aid them with this task, there was an image showing the layout of the keyboard. The percentage of keys they remembered correctly was used as the Awareness score. The Awareness score could have values from 0 to 1, with zero indicating 0% correct keys and one indicating 100% correct keys. Afterwards, participants were told to indicate how they remembered the combinations they wrote down. They were able to choose between: a) I remembered the combination of the letters; b) I remembered the positions of the keys; c) I remembered the positions of the squares on the screen; d) I pressed the keys in my mind; e) I pressed the keys on the tabletop; and f) Differently, namely:

Then, participants' experience with videogames, playing piano, playing other instruments and with various sports was explored with three questions each. First, it was asked when participants made their experiences with the activity in question. They could choose between still being active, having been active until 3 years ago and more than 3 years ago. Second, it was inquired how many hours a week participants spent with a given activity. They were able to choose between under 1 hour, 1 to 7 hours and over 7 hours. Lastly, participants indicated how much time they had spent doing a particular activity in total. They could choose between under 1 year, between 1 and 5 years and under 5 years. Each sub question was rated with a number score from zero (no experience at all with the activity) to three (the answer that indicated the most experience with an activity). The mean of the score of the three sub-questions per activity then yielded the Proficiency score for each activity. These scores were then checked for their correlation to the participants’ performance in Block 8.

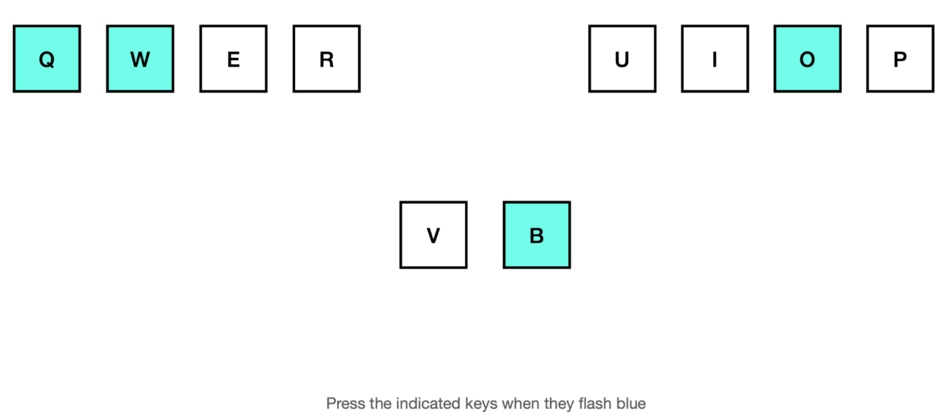
Finally, participants were asked to indicate if they were smokers, if they had consumed alcohol in the last 24 hours and whether they were dyslexic or stuttered. Furthermore, they were asked to state which of their hands was the dominant one.

Task

First, participants were greeted with a screen explaining to them how the task worked and where to place their fingers. They were told to press the spacebar when they had understood what they had to do. Then, participants were presented with a screen (see Figure 1) showing boxes representing keyboard keys (Q,W,E,R,V,B,U,I,O,P). On the same screen, a message was shown telling participants to press the keys that would be flashing. When the keys flashed in cyan, participants pressed them down and their performance on reaction time and errors was recorded (see Figure 1).

Figure 1

Screen of the experiment when the prompt for an exemplar chord is displayed



The task consisted of eight blocks. Seven blocks were dedicated to practice and the last Block was used as a test Block. In the practice Blocks, participants were exposed to two unique chords. These chords varied between participants and always included two fingers on each hand (for the exact composition of chords see Appendix 2). The left hand was always responsible for the Q, W, E, R and V keys. The right hand always performed chords using the B, U, I, O, and P keys. The fingers used for chords were counterbalanced across participants (see Appendix 2). This was done to exclude possible effects of individual fingers and finger combinations, caused by different levels of independence or enslavement of fingers.

In Block 8, participants were not only prompted to execute the two chords they practiced but also had to execute two chords that were completely novel to them. Additionally, they had to execute mirrored versions of the practiced chords. 1-Hand Mirror Chords consisted of the mirrored version of a practiced chord per hand. This means that if for example the right hand practiced pressing the B and U Keys, it would now have to press the O and P keys. 2-Hand Mirror Chords were a version of practiced chords that was mirrored between the hands. Following this logic, in an example where the practiced chord had the right hand press the O and P keys, the left hand would now have to press the Q and W keys.

Design

The main Independent Variable used to answer the hypothesis was Chord-type, meaning the test conditions Practiced, Novel ,1-Hand Mirror and 2-Hand Mirror in Block 8. The main Dependent Variables were the performance measurements Reaction Time (RT) and Error Rate. RT was measured as the difference in time between the stimulus onset time and the moment when the desired keys were correctly pressed. The Error Rate equated to the proportion of correctly executed chords to chords that contained at least one type of error. The types of errors that could happen were timing-errors, miss-errors or no-input errors. These error types describe inputs where the keys were not pressed simultaneously (timing-error), inputs where at least one wrong key was pressed or a desired key was missing (miss-error), and inputs where there was no input (no-input error).

The seven practice blocks consisted of 160 trials each, separated into two sub-blocks with 80 trials each with a quick break in between. Over the seven blocks, this means that each chord was practiced 560 times (2 chords in total). The eight Block consisted of 208 trials separated into two sub-blocks. Each condition had two chords associated with it and each of the chords was executed 26 times during block 8.

Procedure

The study took between 2.5 and 3 hours. After arriving, participants were welcomed and given spoken instructions. Then, their participant ID and the date and time of their participation were recorded. The participants were asked to leave their phones outside of the experimental room, to prevent distraction. Then, participants sat down in front of the computer and were subjected to the seven practice blocks of the experiment. The blocks took about 15 minutes each and were separated by breaks of 4 minutes, where participants were able to relax. After the break, the researcher entered the room to start the next block. Following the seven practice blocks, participants were asked to fill out a questionnaire (see Appendix 3). Then, the eighth block of the experiment was started by the researchers. After finishing Block 8, participants were thanked for their participation, provided with a debriefing and were able to leave.

Data Analysis

Four different analyses of variance were conducted using the afex package in R-Studio (*R: The R Project for Statistical Computing*, n.d.), to examine if there is a significant difference in Errors and RT between blocks or test-conditions. The Reaction times across the first seven trial rounds and the reaction times per test condition in Block 8 (1-Hand Mirror, 2-Hand Mirror, Novel, Practiced Chords) were analyzed in separate ANOVAS. Similarly, the arcsine transformed error proportions for the first seven trial rounds and per test condition in round eight received separate analyses of variance. Moreover, a planned pairwise comparison using the emmeans package was utilized to contrast the Reaction Times per test condition. Furthermore, the mean RT per round and Proportion of Errors per round in the first seven trials was calculated. Boxplots were created based on these means. Statistical significance was set at an alpha of $\alpha = 0.05$. Also, to exclude other explanations for the observed effects, participants' Proficiency scores for gaming, piano, other musical instruments and sports were checked for their correlation to their performance on RT and Errors in Block 8 in each of the conditions. Furthermore, participants' Awareness score was correlated to the same Performance scores. Lastly, the correlations of the Performance scores to self-reported stuttering, dyslexia and handedness were checked. The specific code that was used to analyze the data in R-studio can be found in Appendix 4.

Results

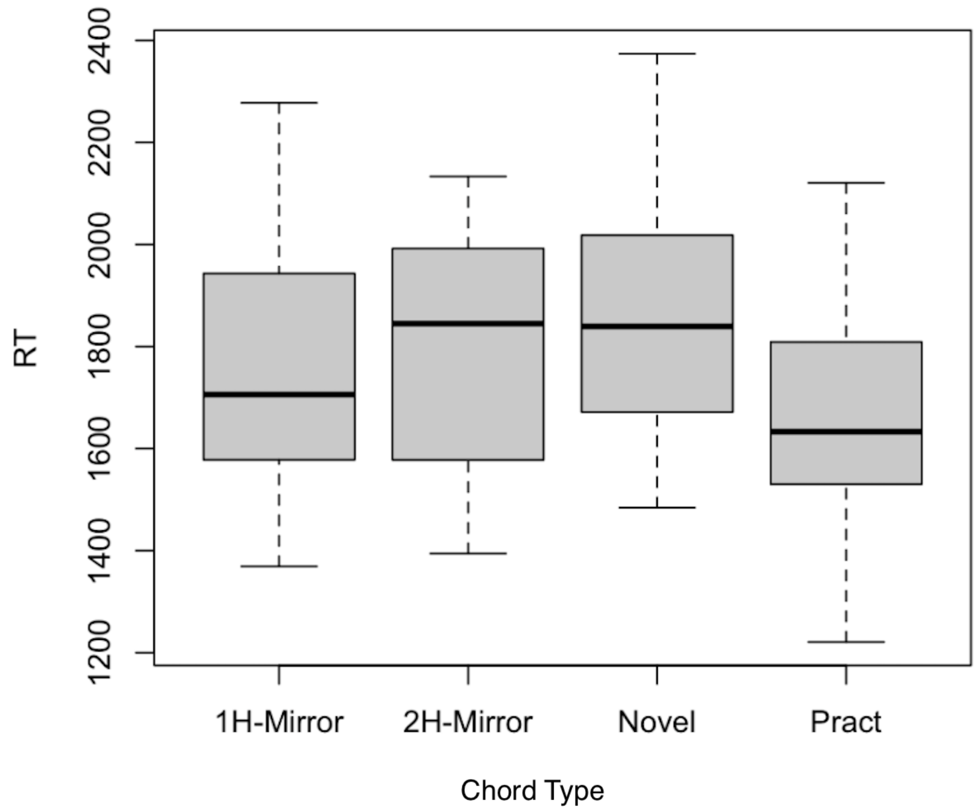
Main analyses

A within-subject ANOVA was conducted for Block 8. This analysis included the four-level independent variable Chord-type and the dependent variable RT. The ANOVA yielded a significant main effect of Chord-type, $F(3,33)=6.49$ $p < .005$, $\eta_p^2 = 0.37$, showing that there is indeed a significant difference between test conditions. Additional pairwise planned comparisons showed that there was a significant difference between the Novel and Practiced group with the mean of the Novel group being estimated 200 ms higher, $t(11)=3.976$ $p = .010$. Furthermore, there was a significant difference found between the 2-Hand mirror Chord-Type and the Practiced Chord-Type. The mean RT of the 2-Hand Mirror Chord-Type was 144.2 ms higher than that of the Practiced Chord-Type, $t(11) = 3.136$, $p = 0.041$. There was no significant difference found between any of the other Chord-Types. The means and spread of the reaction times per Chord-Type can be seen in Figure 4.

Then, an ANOVA exploring the difference in error proportions across Chord-Types in Block 8 was conducted. In the analysis, the Independent Variable Chord-type and the Dependent Variable Errors were compared within subjects. The analysis showed no significant main effect of Chord-type $F(3,33)= 0.55$, $p = 0.65$ $\eta_p^2 = 0.05$, indicating that there is no significant difference in error proportions across test conditions.

Figure 2

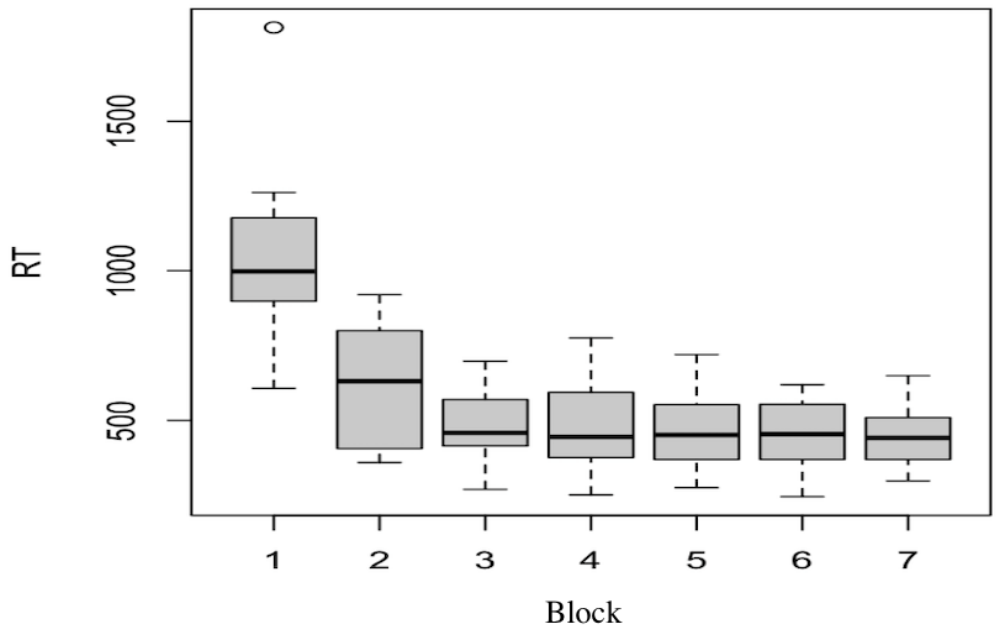
Boxplot of Mean Reaction Times(ms) per Test Condition in Block 8



To test the development of reaction times across the first seven practice blocks, a within-subjects ANOVA with the seven-level independent variable Block and the dependent variable RT was conducted. The analysis found a significant main effect of Block, $F(6,66)= 33.0$ $p < .005$, $\eta_p^2 = 0.75$, indicating that Reaction Times reduced with practice. Looking at Figure 3 reveals that Block 1 had the slowest RT with a mean of 1046 ms and that round seven had the quickest RT with a mean of 444 ms.

Figure 3

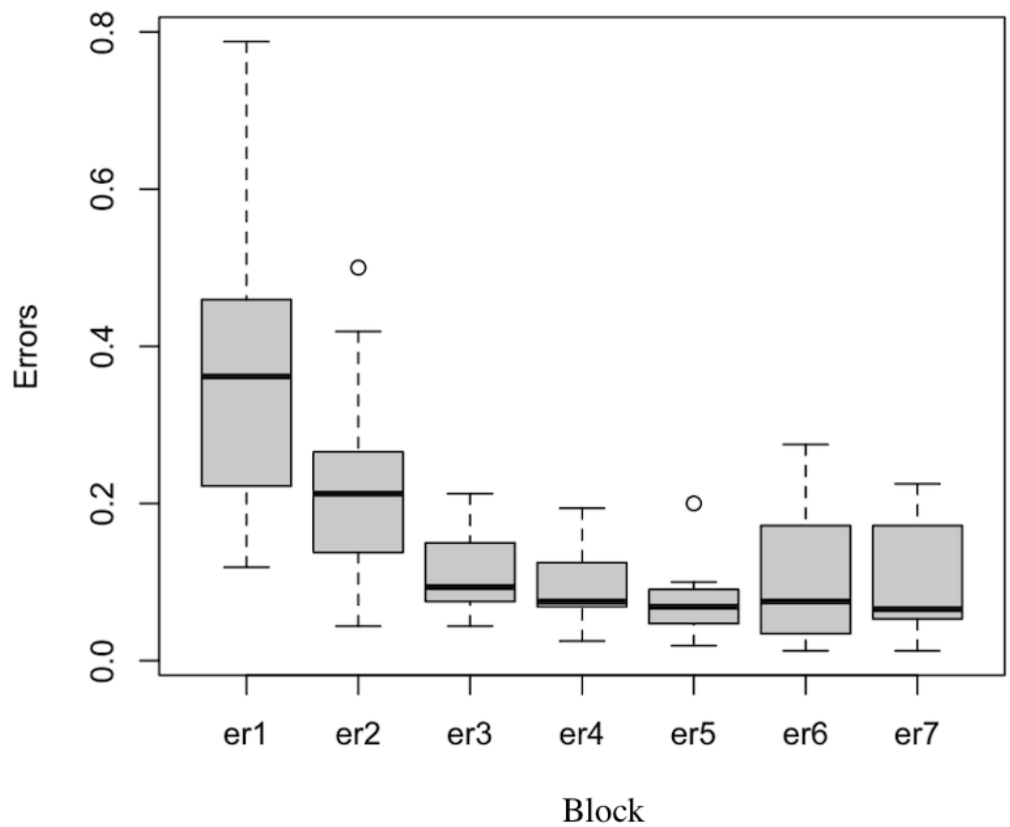
Boxplot of Reaction Times per Block of Blocks 1-7



For the purpose of testing the development of the proportion of errors across the seven practice trials, a within-subjects Anova with the seven level Independent Variable Block and the Dependent Variable Errors was conducted. For this analysis the arcsine transformed proportions of errors were used. The analysis found a significant main effect of Block, $F(6,66)=17.72$ $p<.005$, $\eta_p^2 =0.62$, indicating that the proportion of errors generally reduces across the seven Blocks but with the lowest errors in Block 5. The development error proportions across the Blocks can be seen in more detail in Figure 4.

Figure 4

Proportion of errors to successful inputs per Block



Effects of other variables

To ensure that the observed effects stem from the experimental manipulations, some other effects were tested. There were no significant correlations found between any of the Proficiency scores (Video Games, Piano, other Instruments, Sports) and the RT or error performance in any of the Test Conditions in Block 8. P-values for the correlations ranged between 0.13 and 0.91. Furthermore, there was also no significant correlation between participant´s performance on the awareness test and their performance in either of the four test-conditions in Block 8. P-values for these correlations ranged between 0.61 and 0.94. It must be noted, however, that most of the participants were aware of the keys they pressed. Of the 13 participants that filled out the questionnaire, 10 remembered all the correct keys. When asked how they remembered the keys, the most common answers were remembering the position of the keys, which was indicated 8 times and remembering the combination of letters, which was indicated 7 times. Less often, people said they pressed the keys in their mind (four times) or on the tabletop (once).

Discussion

The current study explored whether a spatial representation of a chord develops across the hands with bimanual practice (H1) or if a spatial or hand posture-representation is developed per hand and transfers to the other hand of the mirror sequence (H2). To test these hypotheses, participants practiced two bimanual chords for 560 trials each and then tested their performance on versions of these chords that were mirrored within (1-Hand Mirror) or across (2-Hand Mirror) the hands.

There was very limited support found for both hypotheses. This support is not obtained from the main analyses intended to test the hypotheses. Thus, it is necessary to conduct more thorough and methodologically sound follow-up research.

Spatial Representation

Hypothesis 1 is not supported by the main analyses, as there was no significant difference in RT or Error Proportion performance of the 1-Hand Mirror Condition to the Control Conditions. This means that there is no evidence in the data for a spatial representation that facilitates performance. One interpretation of these results is that people simply might not be able to mirror spatial representations. Furthermore, it is also possible that spatial representations do not play a significant role in the execution of chord skill. This would be in line with findings of Verwey (2023), concluding that chord skill is determined by the learning of hand postures and not spatial representations. However, an alternative explanation for the lack of significant evidence of the presence of a spatial representation might be the lack of statistical power. Achieving only a third of its desired participants, the statistical power of the study is severely limited. It might be that significant results could have been obtained with more statistical power, though there is no way to determine this. An indicator, if one is willing to speculate, might be the mean of the 1-Hand Mirror Condition, which is closer to the mean of the practiced condition condition than that of the novel condition. If statistically significant, this finding would indicate the presence of a spatial representation that is able to facilitate performance and be mirrored within the hand. It is, however, not statistically significant and thus can only serve as an indicator to encourage further research with more statistical power. Adding to this point, a vast majority of participants were able to correctly recall all the keys belonging to the chords they had played, which shows that participants had memorized the keys they were pressing. A majority of participants also indicated that they remembered the chords by remembering the positions of keys and the combination of letters. This suggests their ability to remember the chords stemming from the presence of a spatial representation. Still, this is not very strong evidence, mainly because participants' awareness did not correlate significantly with their performance. This is in line with findings by Verwey (2023), where there was also no correlation found between awareness and performance. The article suggests that the explicit knowledge of chord composition is not immediately available but has to be reconstructed from episodic and implicit motoric memory, which is too slow to benefit performance (Verwey, 2023).

Overall, there is no strong, statistically significant evidence to support the presence of a spatial representation that facilitates performance and can be mirrored within the hand. Still, there are some results that enable speculations of the lack of strong evidence being due to low statistical power. Future research with more statistical power may help to provide more unambiguous evidence to reject or support the hypothesis.

Transfer between hands

Hypothesis two also must be rejected based on the results of the study. There was no significant difference found between participants' performance on novel chords and chords mirrored across the hands. This means that there is no direct evidence to suggest that there is a spatial or hand posture representation that can be transferred between the hands in a way that aids performance. Further evidence for this is the 2-Hand Mirror Condition being significantly slower than the Practiced Condition (144.2 ms), with mean reaction times very similar to the Novel Condition (see Figure 2). This finding further suggests that there is no transfer of hand posture or spatial representations to the mirror version of the other hand. This is in line with the study of Verwey (2023), finding no transfer of chord skill to a non-practiced hand configuration, which was not mirrored. It seems that using a mirror version did not change that outcome, further clarifying the absence of transfer.

Limitations

As aforementioned, the main limitation of this study consists of constraints to sample size. Due to difficulties in the acquisition of participants, only a third of the desired sample size of 36 was achieved. This severely limits the statistical power of the experiment and very well might be the reason for the non-significance of more subtle effects, such as those of mirrored chords. A further limitation to the sample is the failure to achieve a balanced dataset. The effects of individual fingers were balanced between participants by distributing chords with various combinations of fingers among sets of 16 participants. This means that 16 participants would have been needed for a balanced dataset. Thus, interfering effects of individual fingers and finger combinations, such as different levels of enslavement, cannot be excluded, as the data that had to be treated as balanced was not actually balanced.

Also, a factor that might have had a negative impact on the data could be fatigue. It can be observed in the data that performance starts to decline after Block 5. Mainly, the proportion of errors started to increase (see Figure 4), while RT performance stagnated (See Figure 3).

Furthermore, many participants mentioned being fatigued in conversation between the blocks. This means that the subjects were not in the optimal condition to perform in the test Block. Thus, their decreased performance across the board might also decrease the difference in performance between test conditions and make it harder to find significant differences between test conditions.

Conclusion

The current study was not able to confirm the presence of a spatial representation that facilitates performance and is able to be mirrored within the hand. However, results indicate that this might have been due to low statistical power. This shows the need for more statistically powerful research that can give clearer answers. Transfer of chord skill to the other hand of the mirror sequence can be rejected more unambiguously through the results of this study. Nevertheless, more statistical power would also help to cement this finding, especially considering that the dataset of the current study was not balanced.

It is instrumental for future research to achieve a larger, balanced dataset to increase statistical power and validity. Furthermore, it might make sense to shorten practice to 5 Blocks, as this was the peak of performance, reducing fatigue. This might help to increase statistical power and make the study more attractive to participants by being shorter, helping with the problems with participant acquisition.

References

Adam, J. J., & Van Gerven, P. W. M. (2021). Proactive motor control within and between hands: Effects of age, motor set, and cue type. *Acta Psychologica*, *212*, 103214. https://doi.org/10.1016/j.actpsy.2020.103214

Dahms, C., Brodoehl, S., Witte, O. W., & Klingner, C. M. (2019). The importance of different learning stages for motor sequence learning after stroke. *Human Brain Mapping*, *41*(1), 270–286. https://doi.org/10.1002/hbm.24793

Häger-Ross, C., & Schieber, M. H. (2000). Quantifying the independence of human finger movements: comparisons of digits, hands, and movement frequencies. *The Journal of Neuroscience*, *20*(22), 8542–8550. https://doi.org/10.1523/jneurosci.20-22-08542.2000

Imagebox. (2023, November 14). *E-Prime® | Psychology Software Tools*. Psychology Software Tools | Solutions for Research, Assessment, and Education. https://pstnet.com/products/e-prime/

Krebs, F., & Asfour, T. (2022). A bimanual manipulation taxonomy. *IEEE Robotics and Automation Letters*, *7*(4), 11031–11038. https://doi.org/10.1109/lra.2022.3196158

Naotoshi Abekawa, Ito, S., & Hiroaki Gomi. (2022). Gaze-specific motor memories for hand-reaching. *Current Biology*, *32*(12), 2747-2753.e6. https://doi.org/10.1016/j.cub.2022.04.065

Qualtrics XM - Experience Management Software. (2023, December 19). Qualtrics. https://www.qualtrics.com/uk/?rid=ip&prevsite=en&newsite=uk&geo=NL&geomatch=uk

R: The R Project for Statistical Computing. (n.d.). https://www.r-project.org

Romano, D., Mioli, A., D'Alonzo, M., Maravita, A., Di Lazzaro, V., & Di Pino, G. (2021). Behavioral and Physiological Evidence of a favored Hand Posture in the Body

Representation for Action. *Cerebral Cortex*, *31*(7), 3299–3310. https://doi.org/10.1093/cercor/bhab011

Schieber, M. H., & Hibbard, L. S. (1993). How somatotopic is the motor cortex hand area? *Science*, *261*(5120), 489–492. https://doi.org/10.1126/science.8332915

Seibel, R. (1963). Discrimination reaction time for a 1,023-alternative task. *Journal of Experimental Psychology*, *66*(3), 215–226. https://doi.org/10.1037/h0048914

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. https://doi.org/10.3758/s13423-014-0773-4

Verwey, W. B. (2023). Chord skill: learning optimized hand postures and bimanual coordination. *Experimental Brain Research*, *241*(6), 1643–1659. https://doi.org/10.1007/s00221-023-06629-2

Van Beek, N., Stegeman, D. F., Van Den Noort, J. C., Veeger, H., & Maas, H. (2018). Activity patterns of extrinsic finger flexors and extensors during movements of instructed and non-instructed fingers. *Journal of Electromyography and Kinesiology*, *38*, 187–196. https://doi.org/10.1016/j.jelekin.2017.02.006

Van Den Noort, J. C., Van Beek, N., Van Der Kraan, T., Veeger, H., Stegeman, D. F., Veltink, P. H., & Maas, H. (2016). Variable and Asymmetric Range of Enslaving: Fingers Can Act Independently over Small Range of Flexion. *PLOS ONE*, *11*(12), e0168636. https://doi.org/10.1371/journal.pone.0168636

Schwartz, D. L., & Heiser, J. (2005). Spatial representations and imagery in learning. In *Cambridge University Press eBooks* (pp. 283–298). https://doi.org/10.1017/cbo9780511816833.018

Wang, Y. F., Zhao, J., Négyesi, J., & Nagatomi, R. (2020). Differences in the Magnitude of Motor Skill Acquisition and Interlimb Transfer between Left- and Right-Handed Subjects after Short-Term Unilateral Motor Skill Practice. *Tohoku Journal of Experimental Medicine*, *251*(1), 31–37. https://doi.org/10.1620/tjem.251.31

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews Neuroscience*, *12*(12), 739–751. https://doi.org/10.1038/nrn3112

Appendix

Appendix 1

Informed Consent

Informed consent

This study aims to examine chord learning using a chord task on a computer keyboard. The study has been approved by the BMS ethics committee of the University of Twente. No risks to participants were detected. Participation is voluntary and you can withdraw from the study at any time by informing the attending researcher. Any personally identifiable data that is collected will not be shared beyond the research team and will be destroyed after the study. You will be followed via camera during the study to help the researcher check when you are done with the various blocks. You will not be recorded. The information that you provide will be used for student reports and perhaps for a journal publication or conference report. The reaction time data that you provide will be anonymously archived in the repository of the Open Science Framework so it can be used for future research and learning.

Contact details of the researchers:
p.schwarzmann@student.utwente.nl
m.hof@student.utwente.nl

Please input your participant ID

I have read and understood the text above and consent to taking part in this research

- I consent
- I do not consent

Appendix 2

Design (Chords per participant and condition)

					practiced chords			The participants must be students who: (a) are between the age of 18 and 35 with normal or corrected eye
		1	2	3	4	5		
KEYS:		Q	W	E	R	V		
left hand		pinky	ring	middle	index	thumb		
KEYS:		B	U	I	O	P		
right hand		thumb	index	middle	ring	pinky		

						CCI all fingers	KEYS RIGHT HAND	CCImrl RH mrl fingers	KEYS LEFT HAND	CCImrl LH mrl fingers
	2-KEY									
12	X	X				2	BU	0	QW	2
13	X		X			6	BI	2	QE	4
14	X			X		6	BO	4	QR	2
23		X	X			4	UI	2	WE	2
24		X		X		8	UO	4	WR	4
15	X				X	4	BP	2	QV	2
34			X	X		4	IO	2	ER	2
25		X			X	6	UP	2	WV	4
35			X		X	6	IP	4	EV	2
45				X	X	2	OP	2	RV	0

no symmetrical chords used

CHORD 1 **notice: the thumbs press different keys**

		PRACTICED						NOVEL					
Participant		left hand	CCI	right hand	CCI	LH	RH	left hand	CCI	right hand	CCI	LH	RH
1	17	L12	2	R35	6	XX---	--X-X	L34	4	R14	6	--XX-	X--X-
2	18	L13	6	R45	2	X-X--	.---XX	L25	6	R23	4	-X--X	-XX--
3	19	L14	6	R12	2	X--X-	XX---	L35	6	R34	4	--X-X	--XX-
4	20	L23	4	R13	6	-XX--	X-X--	L45	2	R25	6	.---XX	-X--X
5	21	L34	4	R14	6	--XX-	X--X-	L12	2	R35	6	XX---	--X-X
6	22	L25	6	R23	4	-X--X	-XX--	L13	6	R45	2	X-X--	.---XX
7	23	L35	6	R34	4	--X-X	--XX-	L14	6	R12	2	X--X-	XX---
8	24	L45	2	R25	6	.---XX	-X--X	L23	4	R13	6	-XX--	X-X--
9	25	L12	2	R35	6	XX---	--X-X	L34	4	R14	6	--XX-	X--X-
10	26	L13	6	R45	2	X-X--	.---XX	L25	6	R23	4	-X--X	-XX--
11	27	L14	6	R12	2	X--X-	XX---	L35	6	R34	4	--X-X	--XX-
12	28	L23	4	R13	6	-XX--	X-X--	L45	2	R25	6	.---XX	-X--X
13	29	L34	4	R14	6	--XX-	X--X-	L12	2	R35	6	XX---	--X-X
14	30	L25	6	R23	4	-X--X	-XX--	L13	6	R45	2	X-X--	.---XX
15	31	L35	6	R34	4	--X-X	--XX-	L14	6	R12	2	X--X-	XX---
16	32	L45	2	R25	6	.---XX	-X--X	L23	4	R13	6	-XX--	X-X--
		CCI:	4,5		4,5								

P4a

CHORD 2

		PRACTICED						NOVEL					
Participant		left hand	CCI	right hand	CCI	LH	RH	left hand	CCI	right hand	CCI	LH	RH
1	17	L14	6	R12	2	X--X-	XX---	L35	6	R34	4	--X-X	--XX-
2	18	L23	4	R13	6	-XX--	X-X--	L45	2	R25	6	.---XX	-X--X
3	19	L34	4	R14	6	--XX-	X--X-	L12	2	R35	6	XX---	--X-X
4	20	L25	6	R23	4	-X--X	-XX--	L13	6	R45	2	X-X--	.---XX
5	21	L35	6	R34	4	--X-X	--XX-	L14	6	R12	2	X--X-	XX---
6	22	L45	2	R25	6	.---XX	-X--X	L23	4	R13	6	-XX--	X-X--
7	23	L12	2	R35	6	XX---	--X-X	L34	4	R14	6	--XX-	X--X-
8	24	L13	6	R45	2	X-X--	.---XX	L25	6	R23	4	-X--X	-XX--
9	25	L14	6	R12	2	X--X-	XX---	L35	6	R34	4	--X-X	--XX-
10	26	L23	4	R13	6	-XX--	X-X--	L45	2	R25	6	.---XX	-X--X
11	27	L34	4	R14	6	--XX-	X--X-	L12	2	R35	6	XX---	--X-X
12	28	L25	6	R23	4	-X--X	-XX--	L13	6	R45	2	X-X--	.---XX
13	29	L35	6	R34	4	--X-X	--XX-	L14	6	R12	2	X--X-	XX---
14	30	L45	2	R25	6	.---XX	-X--X	L23	4	R13	6	-XX--	X-X--
15	31	L12	2	R35	6	XX---	--X-X	L34	4	R14	6	--XX-	X--X-
16	32	L13	6	R45	2	X-X--	.---XX	L25	6	R23	4	-X--X	-XX--

is there also transfer to mirrored chord executed with both hands?
after extended practice and 2 skilled hands

MIRROR - ACROSS HANDS

left hand	CCI	right hand	CCI	LH	RH
L13	6	R45	2	X-X--	---XX
L12	2	R35	6	XX---	--X-X
L45	2	R25	6	---XX	-X--X
L35	6	R34	4	--X-X	--XX-
L25	6	R23	4	-X--X	-XX--
L34	4	R14	6	--XX-	X--X-
L23	4	R13	6	-XX--	X-X--
L14	6	R12	2	X--X-	XX---
L13	6	R45	2	X-X--	---XX
L12	2	R35	6	XX---	--X-X
L45	2	R25	6	---XX	-X--X
L35	6	R34	4	--X-X	--XX-
L25	6	R23	4	-X--X	-XX--
L34	4	R14	6	--XX-	X--X-
L23	4	R13	6	-XX--	X-X--
L14	6	R12	2	X--X-	XX---

there was transfer to mirrored chord of the other hand
transfer when each hand performs a mirrored chord after extended practice and 2 skille

MIRROR- PER HAND

left hand	CCI	right hand	CCI	LH	RH
L45	2	R13	6	---XX	X-X--
L35	6	R12	2	--X-X	XX---
L25	6	R45	2	-X--X	---XX
L34	4	R35	6	--XX-	--X-X
L23	4	R25	6	-XX--	-X--X
L14	6	R34	4	X--X-	--XX-
L13	6	R23	4	X-X--	-XX--
L12	2	R14	6	XX---	X--X-
L45	2	R13	6	---XX	X-X--
L35	6	R12	2	--X-X	XX---
L25	6	R45	2	-X--X	---XX
L34	4	R35	6	--XX-	--X-X
L23	4	R25	6	-XX--	-X--X
L14	6	R34	4	X--X-	--XX-
L13	6	R23	4	X-X--	-XX--
L12	2	R14	6	XX---	X--X-

MIRROR - ACROSS HANDS

left hand	CCI	right hand	CCI	LH	RH
L45	2	R25	6	---XX	-X--X
L35	6	R34	4	--X-X	--XX-
L25	6	R23	4	-X--X	-XX--
L34	4	R14	6	--XX-	X--X-
L23	4	R13	6	-XX--	X-X--
L14	6	R12	2	X--X-	XX---
L13	6	R45	2	X-X--	---XX
L12	2	R35	6	XX---	--X-X
L45	2	R25	6	---XX	-X--X
L35	6	R34	4	--X-X	--XX-
L25	6	R23	4	-X--X	-XX--
L34	4	R14	6	--XX-	X--X-
L23	4	R13	6	-XX--	X-X--
L14	6	R12	2	X--X-	XX---
L13	6	R45	2	X-X--	---XX
L12	2	R35	6	XX---	--X-X

MIRROR- PER HAND

left hand	CCI	right hand	CCI	LH	RH
L25	6	R45	2	-X--X	---XX
L34	4	R35	6	--XX-	--X-X
L23	4	R25	6	-XX--	-X--X
L14	6	R34	4	X--X-	--XX-
L13	6	R23	4	X-X--	-XX--
L12	2	R14	6	XX---	X--X-
L45	**2**	**R13**	6	---XX	X-X--
L35	**6**	**R12**	2	--X-X	XX---
L25	6	R45	2	-X--X	---XX
L34	4	R35	6	--XX-	--X-X
L23	4	R25	6	-XX--	-X--X
L14	6	R34	4	X--X-	--XX-
L13	6	R23	4	X-X--	-XX--
L12	2	R14	6	XX---	X--X-
L45	**2**	**R13**	6	---XX	X-X--
L35	**6**	**R12**	2	--X-X	XX---

ACTUAL BALANCED CHORDS:
killed hands?

Participant	P4a	P4aC	P4b	P4bC	N4a	N4aC	N4b	N4bC	M2a	M2aC	M2b	M2bC	M1a	M1aC	M1b	M1bC
1	L12R35	8	L14R12	8	L34R14	10	L35R34	10	L13R45	8	L45R25	8	L45R13	8	L25R45	8
2	L13R45	8	L23R13	10	L25R23	10	L45R25	8	L12R35	8	L35R34	10	L35R12	8	L34R35	10
3	L14R12	8	L34R14	10	L35R34	10	L12R35	8	L45R25	8	L25R23	10	L25R45	8	L23R25	10
4	L23R13	10	L25R23	10	L45R25	8	L13R45	8	L35R34	10	L34R14	10	L34R35	10	L14R34	10
5	L34R14	10	L35R34	10	L12R35	8	L14R12	8	L25R23	10	L23R13	10	L23R25	10	L13R23	10
6	L25R23	10	L45R25	8	L13R45	8	L23R13	10	L34R14	10	L14R12	8	L14R34	10	L12R14	8
7	L35R34	10	L12R35	8	L14R12	8	L34R14	10	L23R13	10	L13R45	8	L13R23	10	L45R13	8
8	L45R25	8	L13R45	8	L23R13	10	L25R23	10	L14R12	8	L12R35	8	L12R14	8	L35R12	8
9	L12R35	8	L14R12	8	L34R14	10	L35R34	10	L13R45	8	L45R25	8	L45R13	8	L25R45	8
10	L13R45	8	L23R13	10	L25R23	10	L45R25	8	L12R35	8	L35R34	10	L35R12	8	L34R35	10
11	L14R12	8	L34R14	10	L35R34	10	L12R35	8	L45R25	8	L25R23	10	L25R45	8	L23R25	10
12	L23R13	10	L25R23	10	L45R25	8	L13R45	8	L35R34	10	L34R14	10	L34R35	10	L14R34	10
13	L34R14	10	L35R34	10	L12R35	8	L14R12	8	L25R23	10	L23R13	10	L23R25	10	L13R23	10
14	L25R23	10	L45R25	8	L13R45	8	L23R13	10	L34R14	10	L14R12	8	L14R34	10	L12R14	8
15	L35R34	10	L12R35	8	L14R12	8	L34R14	10	L23R13	10	L13R45	8	L13R23	10	L45R13	8
16	L45R25	8	L13R45	8	L23R13	10	L25R23	10	L14R12	8	L12R35	8	L12R14	8	L35R12	8

Appendix 3

Questionnaire

Page 1 **chording exp. 6**

Participant Number ______________________________

Age ______________________________

Gender F / M / NB ______________________________

Right or left handed ______________________________

Do you smoke? ______________________________

Did you drink alcohol in the last 24 hours? ______________________________

In this experiment you reacted by pressing keys after perceiving a stimulus light. There were a number of different combinations, while other combinations did not occur. Are you able to write down the combinations you have been practicing? (using the
letters ASDF – Space Bar – HJKL)?

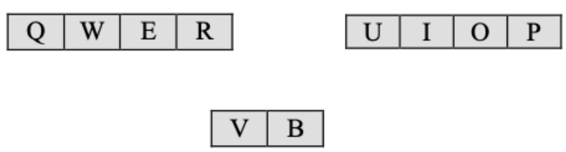


Image of the keys on the keyboard

Page 2

1) What did you do to determine on the previous page of this survey the keys you pressed? (you may circle more than 1 alternative).

a) I remembered the combination of the letters.
b) I remembered the positions of the keys
c) I remembered the positions of the squares on the screen.
d) I pressed the keys in my mind
e) I pressed the keys on the tabletop.
f) Differently, namely:

Below, a number of activities is mentioned. Do you perform these activities? If yes, how long was it ago, and how long have you done this (check 1 alternative per row). Indicate no at the end of the row if you have never done this activity

a) Do you play **video games**?

When?	I still play	until 3 years ago	more than 3 years ago
I play(ed)	< 1 hour a week	1-7 hours per week	> 7 hours a week
totally I played …	< 1 year	1-5 years	> 5 years

b) Do you play **the piano?**

When?	I still play	until 3 years ago	more than 3 years ago
I play(ed)	< 1 hour a week	1-7 hours per week	> 7 hours a week
totally I played …	< 1 year	1-5 years	> 5 years

c) Do you play another **musical instrument**(s), if yes, which one(s)?

When?	I still play	until 3 years ago	more than 3 years ago
I play(ed)	< 1 hour a week	1-7 hours per week	> 7 hours a week
totally I played …	< 1 year	1-5 years	> 5 years

d) Do you play any **sport(s)**, and which**?** (in the case of several sports, please answer for each sport separately)

When?	I still play	until 3 years ago	more than 3 years ago

I play(ed)	< 1 hour a week	1-7 hours per week	> 7 hours a week

totally I played …	< 1 year	1-5 years	> 5 years

e) Do you **stutter?**

no	a little	a fair amount	severely

f) Do you have **dyslexia?**

no	a little	a fair amount	severely

3) Do you have any remarks about the experiment?

Appendix 4

R-Code

```
install.packages("dplyr")
install.packages("afex")
install.packages("emmeans")
install.packages("tidyr")
install.packages("lme4")
install.packages("Matrix")
install.packages("car")
install.packages("stats")
install.packages("ggplot2")
install.packages("broom")
library(tidyr)
library(dplyr)
library(afex)
library(emmeans)
library(lme4)
library(Matrix)
library(car)
library(stats)
library(ggplot2)
library(broom)
#Data Analysis Thesis

#Prep Tables
Table1 <- na.omit(Dataset_thesis)
Table2 <- na.omit(Table2actual2)
Table3 <- na.omit(Table3_actual)
Table4 <- na.omit(Table4_actual)
Table4noArc <- Table4[, c(1,2,3,4,5 )]
colnames(Table4noArc) <- c("Subject","1H-Mirror", "2H-Mirror", "Novel", "Practised")
colnames(Table2) <- as.character(Table2[1, ])
colnames(Table3) <- as.character(Table3[1, ])
colnames(Table4) <- as.character(Table4[1, ])
colnames(awareness_percent) <- as.character(awareness_percent[1, ])
awareness_percent <- slice(awareness_percent, -1)
awareness_percent <- awareness_percent %>%
  mutate_at(vars(`Awareness(correctness percent)`), as.numeric)
```

```
Questionaire_Thesis_Numerscore_ <- merge(awareness_percent,
Questionaire_Thesis_Numerscore_, by = "Subject")
combined_data <- slice(combined_data, -13)
colnames(Questionaire_Thesis_Numerscore_) <-
as.character(Questionaire_Thesis_Numerscore_[1, ])
Table2 <- slice(Table2, -1)
Table3 <- slice(Table3, -1)
Table3 <- Table3 %>%
  mutate_at(vars(Pract,Novel,`1H-Mirror`,`2H-Mirror`), as.numeric)
Table4<- slice(Table4, -1)
Table4 <- Table4 %>%
  mutate_at(vars(Pract_err,Novel_err,`1H-Mirror_err`,`2H-Mirror_err`), as.numeric)
combined_data <- slice(combined_data, -13)
Questionaire_Thesis_Numerscore_ <- slice(Questionaire_Thesis_Numerscore_, -1)
Questionaire_Thesis_Numerscore_ <- Questionaire_Thesis_Numerscore_ %>%
  rename(Subject = `Participant ID`)
combined_data_save <- combined_data
combined_data <- combined_data_save

selected_Table2 <- table2[, c("arc1", "arc2","arc3","arc4","arc5","arc6","arc7")]
selected_columns2 <- Table2[, c(1,9, 10,11,12,13,14,15)]
long_table2 <- gather(selected_columns2, key = "Round", value = "Errors", -"Subject")
selected_Table4 <- Table4[, c(1,6,7,8,9)]
long_table4 <- gather(selected_Table4, key = "Condition", value = "Errors", -"Subject")
as.factor(Table1$Subject)
long_table1 <- gather(Table1, key = "Round", value = "RT", -"Subject")
SelectedTable2NOArc <- Table2[, c(1,2,3,4,5,6,7,8)]
Long_table2_NotArc <- gather(SelectedTable2NOArc, Key= "Round", value = "Errors", -
"Subject")
Long_table2_NotArc <- pivot_longer(
  SelectedTable2NOArc,
  cols = -Subject,
  names_to = "Round",
  values_to = "Errors"
  Long_table4noArc <- pivot_longer(
    Table4noArc,
    cols = -Subject,
    names_to = "Condition",
    values_to = "Errors")
```

```
  as.numeric(Long_table2_NotArc)
  as.numeric(Long_table2_NotArc$Errors)
  as.factor(Long_table2_NotArc$Round)
  #Combine tables
  combined_data <- merge(merge(merge(Table1, Table2, by = "Subject", all = TRUE),
                               Table3, by = "Subject", all = TRUE),
                         Table4, by = "Subject", all = TRUE)
  combined_data <- merge(combined_data, Questionaire_Thesis_Philipp, by ="Subject",
all=TRUE)

#Combined scores for the Questionaire
Questionaire_Thesis_Numerscore_ <- Questionaire_Thesis_Numerscore_ %>%

mutate_at(vars(V_When,`V_H/W`,V_Total,P_When,`P_H/W`,P_Total,I_When,`I_H/W`,I_Total
,S_When,`S_H/W`,S_Total), as.numeric)
Questionaire_Thesis_Numerscore_$MeanScoreVideogames <-
rowMeans(Questionaire_Thesis_Numerscore_[c("V_When", "V_H/W", "V_Total")])
Questionaire_Thesis_Numerscore_$MeanScorePiano <-
rowMeans(Questionaire_Thesis_Numerscore_[c("P_When", "P_H/W", "P_Total")])
Questionaire_Thesis_Numerscore_$MeanScoreInstrument <-
rowMeans(Questionaire_Thesis_Numerscore_[c("I_When", "I_H/W", "I_Total")])
Questionaire_Thesis_Numerscore_$MeanScoreSport <-
rowMeans(Questionaire_Thesis_Numerscore_[c("S_When", "S_H/W", "S_Total")])
#Correlations with questionaire
#RT
MergedTable3 <- merge(Table3, Questionaire_Thesis_Numerscore_, by = "Subject")
cor.test(MergedTable3$Pract, MergedTable3$MeanScoreVideogames)
cor.test(MergedTable3$Pract, MergedTable3$MeanScorePiano)
cor.test(MergedTable3$Pract, MergedTable3$MeanScoreInstrument)
cor.test(MergedTable3$Pract, MergedTable3$MeanScoreSport)
cor.test(MergedTable3$Novel, MergedTable3$MeanScoreVideogames)
cor.test(MergedTable3$Novel, MergedTable3$MeanScorePiano)
cor.test(MergedTable3$Novel, MergedTable3$MeanScoreInstrument)
cor.test(MergedTable3$Novel, MergedTable3$MeanScoreSport)
cor.test(MergedTable3$`1H-Mirror`, MergedTable3$MeanScoreVideogames)
cor.test(MergedTable3$`1H-Mirror`, MergedTable3$MeanScorePiano)
cor.test(MergedTable3$`1H-Mirror`, MergedTable3$MeanScoreInstrument)
cor.test(MergedTable3$`1H-Mirror`, MergedTable3$MeanScoreSport)
cor.test(MergedTable3$`2H-Mirror`, MergedTable3$MeanScoreVideogames)
cor.test(MergedTable3$`2H-Mirror`, MergedTable3$MeanScorePiano)
```

```
cor.test(MergedTable3$`2H-Mirror`, MergedTable3$MeanScoreInstrument)
cor.test(MergedTable3$`2H-Mirror`, MergedTable3$MeanScoreSport)
#Errors
MergedTable4 <- merge(Table4, Questionaire_Thesis_Numerscore_, by = "Subject")
cor.test(MergedTable4$Pract_err, MergedTable4$MeanScoreVideogames)
cor.test(MergedTable4$Pract_err, MergedTable4$MeanScorePiano)
cor.test(MergedTable4$Pract_err, MergedTable4$MeanScoreInstrument)
cor.test(MergedTable4$Pract_err, MergedTable4$MeanScoreSport)
cor.test(MergedTable4$Novel_err, MergedTable4$MeanScoreVideogames)
cor.test(MergedTable4$Novel_err, MergedTable4$MeanScorePiano)
cor.test(MergedTable4$Novel_err, MergedTable4$MeanScoreInstrument)
cor.test(MergedTable4$Novel_err, MergedTable4$MeanScoreSport)
cor.test(MergedTable4$`1H-Mirror_err`, MergedTable4$MeanScoreVideogames)
cor.test(MergedTable4$`1H-Mirror_err`, MergedTable4$MeanScorePiano)
cor.test(MergedTable4$`1H-Mirror_err`, MergedTable4$MeanScoreInstrument)
cor.test(MergedTable4$`1H-Mirror_err`, MergedTable4$MeanScoreSport)
cor.test(MergedTable4$`2H-Mirror_err`, MergedTable4$MeanScoreVideogames)
cor.test(MergedTable4$`2H-Mirror_err`, MergedTable4$MeanScorePiano)
cor.test(MergedTable4$`2H-Mirror_err`, MergedTable4$MeanScoreInstrument)
cor.test(MergedTable4$`2H-Mirror_err`, MergedTable4$MeanScoreSport)
#Awareness
cor.test(MergedTable3$`1H-Mirror`,MergedTable3$`Awareness(correctness percent)`)
cor.test(MergedTable3$`2H-Mirror`,MergedTable3$`Awareness(correctness percent)`)
cor.test(MergedTable3$Pract,MergedTable3$`Awareness(correctness percent)`)
cor.test(MergedTable3$Novel,MergedTable3$`Awareness(correctness percent)`)

cor.test(MergedTable4$`1H-Mirror_err`,MergedTable4$`Awareness(correctness percent)`)
cor.test(MergedTable4$`2H-Mirror_err`,MergedTable4$`Awareness(correctness percent)`)
cor.test(MergedTable4$Pract_err,MergedTable4$`Awareness(correctness percent)`)
cor.test(MergedTable4$Novel_err,MergedTable4$`Awareness(correctness percent)`)


#Demographics
as.character(Questionaire_Thesis_Philipp$Age)
as.numeric(Questionaire_Thesis_Philipp$Age)
AgeTable <- Questionaire_Thesis_Philipp[["Age"]]
as.numeric(AgeTable)
mean(AgeTable)
mean(Questionaire_Thesis_Philipp$Age)
#descriptive analysis
```

```
#means
combined_data$MeanRTColumn <- rowMeans(combined_data[, c("1", "2", "3", "4", "5", "6",
"7")])
combined_data$MeanErrorColumn <- rowMeans(combined_data[, c("er1", "er2", "er3", "er4",
"er5", "er6", "er7")], na.rm = TRUE)
combined_data$MeanColumn <- rowMeans(combined_data[, c("1", "2", "3", "4", "5", "6", "7")])
combined_data <- combined_data %>%
  mutate_at(vars(1:34), as.numeric)
#means of the groups
mean(combined_data[["1H-Mirror"]])
sd(combined_data[["1H-Mirror"]])
mean(combined_data[["2H-Mirror"]])
sd(combined_data[["2H-Mirror"]])
mean(combined_data[["Novel"]])
sd(combined_data[["Novel"]])
mean(combined_data[["Pract"]])
sd(combined_data[["Pract"]])
mean(combined_data[["1H-Mirror_err"]])
sd(combined_data[["1H-Mirror_err"]])
mean(combined_data[["2H-Mirror_err"]])
sd(combined_data[["2H-Mirror_err"]])
mean(combined_data[["Novel_err"]])
sd(combined_data[["Novel_err"]])
mean(combined_data[["Pract_err"]])
sd(combined_data[["Pract_err"]])
#Comparing means
combined_data%>% cor(MeanRTColumn,c(23))
combined_data %>%
  select(MeanRTColumn, `1H-Mirror`) %>%
  cor()

#Anova

# Boxplot
boxplot(RT ~ Condition, data = long_table)
outlierTest(model)
boxplot(RT ~ Round, data = long_table1)
boxplot(Errors ~ Round, data=Long_table2_NotArc)
boxplot(Errors ~ Condition ,data =Long_table4noArc)
```

```
Table4noArc<- mutate(Long_table4noArc, "1H-Mirror_err" = "1H-Mirror", "2H-
Mirror_err"="2H-Mirror", Novel_err = "Novel", Pract_err= "Practised")
Long_table4noArc <- Long_table4noArc %>% mutate_at( "Errors", as.numeric)
as.numeric(Long_table2_NotArc$Errors)
mutate(Table2, er1 = "1", er2="2", er3 = "3", er4= "4", er5= "5", er6= "6", er7= "7" )
#table 3
long_table <- gather(Table3, key = "Condition", value = "RT", -"Subject")
as.factor(long_table$Subject)
model <- aov_car(RT ~ Condition + Error(Subject), data = long_table)
long_table <- long_table %>% mutate_at( "RT", as.numeric)
anova_result <- anova(model)
summary(anova_result)
  #table 2
model2 <- aov_car(Errors ~ Round + Error(Subject), data = long_table2)
as.factor(long_table2$Round)
as.numeric(long_table2$Round)
long_table2 <- long_table2 %>% mutate_at( "Errors", as.numeric)
anova_result2 <- anova(model2)
summary(anova_result2)
summary(model2, es = "p")
 #table4
model4 <- aov_car(Errors ~ Condition + Error(Subject), data = long_table4)
long_table4 <- long_table4 %>% mutate_at( "Errors", as.numeric)
anova_result4 <- anova(model4)
summary(anova_result4)
summary(model4)
 #table1
as.factor(long_table1$Subject)
as.factor(long_table1$Round)
as.numeric(long_table1$Round)
as.numeric(long_table1$Subject)

long_table1$Round <- factor(long_table1$Round, levels = c(1, 2, 3, 4, 5, 6, 7))

model1 <- aov_car(RT ~ Round + Error(Subject), data = long_table1)
model1 <- aov_car(RT ~ Round + Error(1/Subject), data = long_table1)
long_table4 <- long_table4 %>% mutate_at( "Errors", as.numeric)
summary(model1)

#claculate eta squared
```

```
#1
SS_Effect <- anova_resultalt$`num Df`* anova_resultalt$MSE
SS_Error <- anova_resultalt$`den Df`  * anova_resultalt$MSE

# Calculate partial eta-squared
#1
et2.1 <- 3439054/(3439054+1146469)
et2.2 <-5.604/(5.604+3.4796)
et2.3 <- 263699/(263699+447218)
et2.4 <- 0.121/(0.121+2.4036)
eta_squared <- SS_Effect / (SS_Effect + SS_Error)



#corrected p1
p_adjusted1 <- p.adjust(anova_result1$`Pr(>F)`, method = "bonferroni")
p_adjusted2 <- p.adjust(anova_result1$`Pr(>F)`, method = "holm")
p_adjusted3 <- p.adjust(anova_result1$`Pr(>F)`, method = "fdr")

#p2
p_adjusted2.1 <- p.adjust(anova_result2$`Pr(>F)`, method = "bonferroni")
p_adjusted2.2 <- p.adjust(anova_result2$`Pr(>F)`, method = "holm")
p_adjusted2.3 <- p.adjust(anova_result2$`Pr(>F)`, method = "fdr")

#p3
p_adjusted3.1 <- p.adjust(anova_result$`Pr(>F)`, method = "bonferroni")
p_adjusted3.2 <- p.adjust(anova_result$`Pr(>F)`, method = "holm")
p_adjusted3.3 <- p.adjust(anova_result$`Pr(>F)`, method = "fdr")

#p4
p_adjusted4.1 <- p.adjust(anova_result4$`Pr(>F)`, method = "bonferroni")
p_adjusted4.2 <- p.adjust(anova_result4$`Pr(>F)`, method = "holm")
p_adjusted4.3 <- p.adjust(anova_result4$`Pr(>F)`, method = "fdr")

# Create a box plot
 ggplot(augmented_data, aes(x = Round, y = .resid)) +
   geom_boxplot() +
   labs(title = "Reaction time per Round",
        x = "Round",
        y = "Residuals")
```

```
> # Summary of emmeans results
> summary(emmeans_results)
```

```
#planned comparison
emmeans_object <- emmeans(model, "Condition")
pairwise_comparisons <- pairs(emmeans_object)

emmeans_object2 <- emmeans(model1, "Round")
pairwise_comparisons <- pairs(emmeans_object2)
print(emmeans_object2)
```