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Investigating a motor skill: The case of chording

Bachelor thesis

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Abstract

The present study looks into the learning of chords with one or two hands, and the performance of new and practiced chords. Chords are multiple keypresses at the same time, producing one response. For this, 32 participants were recruited and practiced a set of chords with either four fingers of their right hand, or two fingers of both hands during the practice phase. After practicing for eight blocks, the participants performed practiced and new chords with the same and different hand configurations during the test phase. Results showed that chord learning is possible and that overall the group using two hands had a higher reaction time than the group using their right hand. Furthermore, the two groups did have a similar learning curve. Lastly, there is no transfer of the chords to the other hand configuration, which could mean that hand postures are learned instead of the positions of the keys.

Introduction

From the people around us who play musical instruments, it is commonly heard that they have difficulty in playing using two hands instead of one. Think of playing the piano for example, where you can play chords using multiple fingers. Why does it seem more difficult to play using two hands than one hand? A possible explanation which is elaborated on by Kolb and Whishaw (2009), is that there is information coming from the left side of the body and goes to the right side, hemisphere, of the brain. Then the right hemisphere reacts to these inputs and controls the movements of the left side of the body. When both sides of the body have to work together, the hemispheres also have to work together through connections between the two (Kolb & Whishaw, 2009). If the hemispheres have to communicate when using two hands and not when using one hand, it could be there is a difference in reaction times when performing tasks. Therefore, the aim of the present research is to see if there is a difference in improvement and performance time when using two hands, than when only using one hand in pressing multiple keys in reaction to a stimulus.

Diedrichsen and Kornysheva (2015) give the following definition of motor skill learning: "Motor skill learning generally refers to neuronal changes that allow an organism to accomplish a motor task better, faster, or more accurately than before" (p.227). Seibel (1962) investigated chording, by using a keyboard with five keys, with stimulus lights that corresponded with the keys. Reaction Time (RT) was used to measure the moment from when the stimulus appeared until the right keys where pressed and also released. Results showed that the RT decreased while practicing, while the error rate did not increase (Seibel, 1962).

There are a few studies that adapted the classic chording task of Seibel (1962), to investigate skill acquisition (Guest, Sime, & Green, 1972; Hazeltine, Aparicio, Weinstein, & Ivry, 2007; Wifall, McMurray, & Hazeltine, 2014). Wifall et al. (2014) modified the chording task to see if similarity between the chords affects learning. With similarity they mean that the chord that is supposed to be pressed, has similar stimuli to another possible or learned chord. They did three experiments in which participants practiced and performed chords using two hands. The results showed that similarity has an influence on practiced items, namely that similar items to the already learned items can be learned quicker. However, competition can cause that basic items similar to the practiced item are mistakenly activated and interfere with the correct response. Competition can occur because the chords are similar, so another practiced chord is activated instead of the correct chord (Wifall et al., 2014). Guest et al. (1972) used an adapted chording task to investigate the relation of errors to how the correct response should have been. They found that the following factors played a role: the delta value (the difference between the separation of fingers during required response and the separation of fingers during actual response), mirroring of correct and actual response and the presence of a finger used in both (Guest et al., 1972). Hazeltine et al. (2007) studied configural response learning in four experiments. With configural response they mean that different keys have to be pressed at the same time, forming one response and thus identical to what is meant by a chord in the present study. All experiments made use of an adapted chording task. In some tasks only one hand was used, and in others both hands. Results from Experiments 1, 2 and 4 show that there is configural learning, chords are learned and coded as one unit or response. So they found that chord learning is chord-specific, learning postures instead of individual elements of the posture. However, there was some learning on individual element level which could be due to similarity of the chords (Hazeltine et al., 2007).

Drake and Palmer (2000) tested pianists with different skill levels on how they learned a new musical piece. They investigated the improvements in accuracy and speed, but it has to be taken into account that in a musical piece not every note has to be played as fast as possible, but rather at the correct time. Participants with different skill levels played different pieces to match their skill, easier pieces were only for playing with one hand, more difficult pieces using both hands. Their findings were in line with the power function, speed and accuracy both improved with practice, and pianists with higher skill levels made fewer mistakes and played faster. While this experiment did not use the classic chording task used by Seibel (1962), their experiment looks at motor skill acquisition of playing piano and thus also chords (Drake & Palmer, 2000).

These aforementioned studies (Drake & Palmer, 2000; Guest et al., 1972; Hazeltine et al., 2007; Wifall et al., 2014), looked into skill acquisition while pressing keys, but did not look at the difference in learning between practicing with one hand or two hands. Cardoso de Oliveira (2002) adapted the multi-level crosstalk model of Rinkenauer (2000), on the basis of ideas from Heuer, Kleinsorge, Spijkers, and Steglich (2001), Marteniuk and MacKenzie (1980) and Preilowski (1975). This resulted in a model that suggests actions for the two arms that are planned separately, but interact on a high- and low-level. The high-level interaction, probably through a callosal connection, could make the two different plans seem like a common plan, but still specifying the different elements for the two arms. The lower level is more related to the motor plans being carried out. However, this model cannot cover the underlying processes or behavioural phenomena. In sum, the high level interaction is the planning of the movement, while the low level is the execution of the movement (Cardoso de Oliveira, 2002).

In their study, Rice, Tunik, Cross, and Grafton (2007) investigated grasping movements of the left and right hand and how the hemispheres control these movements. To study this, they used transcranial magnetic stimulation (TMS) of the left and right anterior intraparietal sulcus (aIPS) during grasping. Their results showed that when the left aIPS was stimulated using TMS, only grasping with the right hand was disturbed and vice versa for the right aIPS (Rice et al., 2007). Even though grasping is not similar to pressing keys, this study is important for the present study to show that when using the one hand, only one hemisphere is involved.

In their second experiment, Hazeltine et al. (2007) performed an edited version of the chording task by comparing responses between using one hand (unimanual) and two hands (bimanual). During the experiment, only chords consisting of two elements were tested. The results showed that there is configural learning in using one hand and using two hands. However, they also found that in the trials with two hands the reaction time was much longer than in the trials using one hand. This was not due to differences in the physical distance, which they defined as the number of fingers between the keys that had to be pressed for a chord (Hazeltine et al., 2007). Gerloff and Andres (2002) also looked at bimanual key pressing. In their experiment they first let the participant press short key sequences with each hand separately, then later they had to perform the sequences for the separate hands togethers. Next to keypresses, they also used EEG and EMG for measurements. Their results showed that in the sequence learning with one hand, there was no enhanced interhemispheric functional coupling, but this was present in early learning using both hands (Gerloff & Andres, 2002).

A limiting factor in chording studies can be the biomechanical limitations of fingers when pressing chords. In a study by Van den Noort et al. (2016), they found that fingers cannot move completely independent without that other fingers, mostly neighbouring, also move. Specifically, they found that the index finger could move most independently from the other fingers. They also found that the middle and ring finger suffer most when other fingers move, as in that they are forced to then move in accordance to the neighbouring fingers. So when the little finger moves, the ring finger is forced to move with it. This same effect was found for the middle finger when the ring and index finger are moved (Van den Noort et al., 2016).

In the present study, participants have practiced chords with either one, two, or three fingers at the same time. In the practice phases, they practiced the chords with either four fingers of one hand, or two fingers of two hands. During this phase they practiced six chords in total, which took approximately 2.5 hours including breaks. In the test phase, they performed familiar and unfamiliar chords, with both one and two hands for approximately 15 minutes.

Based on the results that show how the hemispheres have to work together through connections in the brain (Kolb & Whishaw, 2009) and the results from a study by Gerloff and Andres (2002) it was expected that when pressing chords with two hands there is interaction between the two hemispheres, while with pressing chords with one hand this is not the case. Therefore, the first expectation was that performance and improvement with practice differs between learning in one hand and two hands, thus there will be different learning curves for the two hand groups. With this, there is also the expectation that the learning of chords is possible. The third expectation was that the group using two hands will have a higher average reaction time, because the two hemispheres have to coordinate the interlimb movements. Hazeltine et al. (2007) found that the learning of chords is chord-specific, which is why lastly it was expected that there was no transfer of chords to the other hand configuration, meaning hand postures are learned instead of the position of the keys (spatial learning).

Methods

Participants

Thirty-two participants voluntarily participated in this study (*M*age=21.52, *SD*age=2.58), of which one participant had to be excluded due to being an extreme outlier in the amount of errors made. All participants were right-handed, non-smokers and did not drink alcohol in the 24 hours preceding the experiment. The experiment was approved by the faculty of Behavioural, Management and Social Sciences (BMS) ethics committee of the University of Twente, and the participants signed an informed consent before starting the experiment. In return for participation in the study, participants could receive course credits when signed up for participation through the corresponding system.

Materials

The participant would use the Dell OptiPlex 7050 (Dell Technologies Inc., Round Rock, TX, USA) computer present in the cubicle. The keyboard was a PS2 Logitech Deluxe 250 (Logitech, Newark, CA, USA), which was sometimes reported as sturdy when pressing buttons by participants. The AOC (AOC International, Taipei, Taiwan) monitor size was 24 inch, and the screen displayed at a refresh rate of 144Hz with FreeSync (Advanced Micro Devices, Inc., Austin, TX, USA) enabled. The stimuli and instructions were displayed on the computer screen. Participants could use keyboard wrist resting pads, for one or both hands if they wanted. Almost every participant started to use this from the start, or somewhere during the experiment. On the left side of the participant, there was a window with the curtain ¾ down to minimise distraction but still letting in sunlight. For every session, the same set-up was used. Paper materials included: twice the written informed consent, an information sheet and the awareness questionnaire. Lastly, the program used for the experiment was programmed in E-Prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA, USA).

Task

In total, the experiment contained nine blocks. The first 8 blocks included the practice trials, and each of these blocks were divided into two. During the subblock 90 stimuli were presented to the participant. The ninth block was the test block and was divided into four subsections of which each had 42 stimuli. Between the subblocks, there was a short break of 30 seconds after which it automatically continued. At the end of the total block, there was a break of 5 minutes. During both breaks, a countdown was displayed on the screen. During the practice trials, the participant had to either use their index, middle, ring and little finger from their right hand or their index and middle fingers from both hands. On the screen, the letters "C", "V", "B" and

“N” were shown, and when a letter turned blue, the participant had to press the corresponding key on the keyboard. The table with the chord design used can be found in Appendix A. During the practice phase, the participants were taught two one-key responses and two two-keys and two three-key chords. The system would give feedback to the participant directly after the keys had been pressed. The system could report: nothing when no mistakes were made, a timing error, a miss and a false hit. A timing error occurred when the keys were not pressed at the same time. The maximum difference between the first and the last keypress to still be seen as one correct chord was 50 ms. Next to this, other possible errors were a false hit, so pressing the wrong key, and a miss, which was not hitting the right key. Time between the placeholder and stimuli was non-aging and could be between 500 and 2000 ms. After block 8, the participant was given an awareness questionnaire. The questions asked about age, if they were right or left handed, if the participants smoked or drank alcohol in the last 24 hours. Then there was a question where the participant had to recall the key combinations of the practiced chords. On the back of the paper, which could only be viewed after the recalling of chords, there was a multiple choice (plus an option to add own answer) question about how the participant recalled the chords. The options to choose from were: a) I remembered the order 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 table top. Lastly, the participant could write down remarks on the form.

Procedure

The experimenter welcomed the participant and started with introducing the research. First, she asked if the participant was right-handed, was non-smoking and if they drank alcohol the 24 hours preceding the experiment. The experimenter provided spoken and written instruction about the study and its procedure. It was explained that there would be nine blocks in total, and that there would be a break of five minutes between the blocks. In the break they could relax, read, walk or come to the experimenter to chat if they wanted. The experimenter then started the program, entered the participant number and block number and the participant could start with the first block. At the start of every new block, the experimenter restarted the program and entered the participant number and block number, and then left the room. Then, the participant received an information sheet, with more information about the study. After reading the sheet, the participant had time to ask questions. After the questions, an informed consent was given and signed in duplicate so the participate could take an informed consent home. After 8 blocks, the experimenter entered the cubicle to give the awareness questionnaire and stayed to answer questions. After the awareness questionnaire, the last test block was explained to the participant. When the last block was finished, the program closed automatically, and the participant could ask questions to the researcher if they wanted to. The participant was thanked for their participation, and where applicable would receive their credit points later through the university's course credit system.

Data analysis

The dependent variable was reaction times or errors. For analyses on the RTs and errors for the practice phases, first a mean of all reaction times per participant was calculated. Then a mixed ANOVA with descriptive statistics, estimates of effect size and homogeneity tests were executed. The factors, with the amount of levels between brackets, of the mixed ANOVA were Block(8), number of Fingers(3) and Chord Difference(2) and the between subjects variable was the Hand Group, which could either be using the right hand or using two hands. There were 8 separate blocks in which the participant could practice, which was meant by Block(8). With Fingers(3) was meant the number of fingers they had to press during the execution of a response, which could either be one, two or three fingers. Since the participants had to perform six chords, there were two chords per number of fingers. Thus, the Chord Difference(2) were the two different options for each number of fingers that were used. For the analyses on the RTs and errors of the test phase, a similar mixed ANOVA was executed. The only difference was in the factors, which were number of Fingers(3), Familiar and Unfamiliar Chords(2), Hand Configuration(2) and Chord Difference(2). Familiar chords were the chords practiced during the practice phase and unfamiliar chords were a set of six new chords presented during two out of four test phase subblocks. Also, during two out of four subblocks, participants had to switch to the other hand condition, so the Hand Configuration(2) could either be the same as during the practice phase or the different configuration. Lastly, some effects and interaction effects had a p-value below 0.05 on Mauchly's Test of Sphericity, which showed that there was no sphericity for these results. For these effects the degrees of freedom and thus the p-values were corrected using the Greenhouse-Geisser correction.

Results

Practice phase RTs

A mixed ANOVA was executed on the Practice phase RTs, with the Hand Group as between subjects variable. Furthermore, the factors were Block(8), number of Fingers(3) and Chord Difference(2).

Firstly, the group using two hands were faster than the group using only their right hand, $F(1,29)=18.03$, $p<.001$, $\eta_p^2=.38$. The corresponding means in RTs in milliseconds were calculated for the group using two hands (M=515, SD=54) and the group using only their right hand(M=623, SD=88).

In Figure 1, the average reaction time can be seen per Block, with different lines for the two Hand Groups. There was a significant difference between the Blocks, $F(7, 203)=23.41$, $p<.001$,$\eta_p^2=.45$, but this was not different between the different Hand Groups, $F(7, 203)=0.34$, $p=.93$,$\eta_p^2=.01$. As can be seen in Figure 1, at the start the reaction times are decreasing for both groups more quickly than in later blocks. Furthermore, at the last blocks the reaction times stopped decreasing.

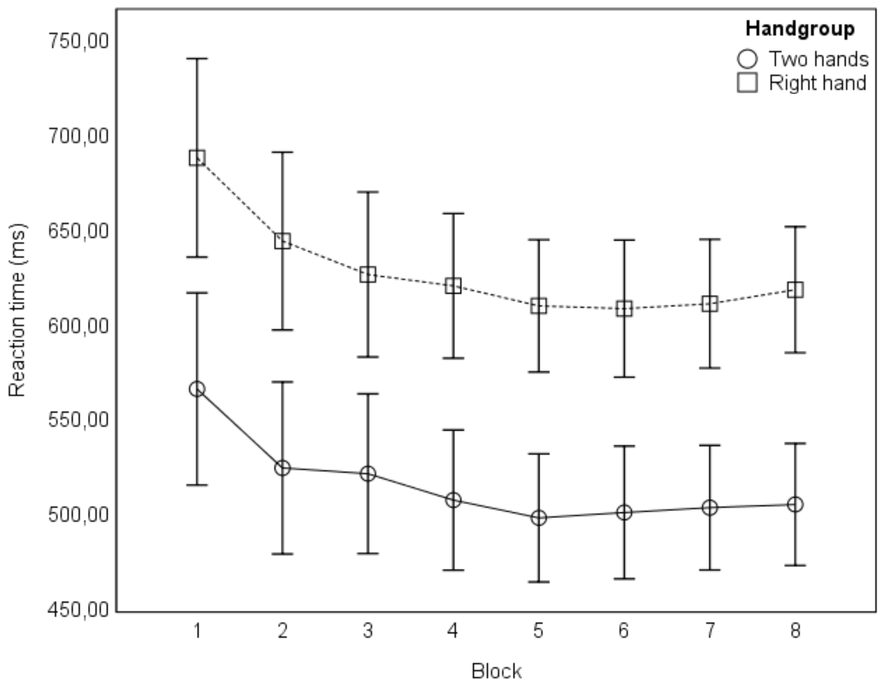

Figure 1 The reaction times in milliseconds showing the development over the practice blocks. During the 8 practice blocks the participants had practiced a set of 6 chords. The two different lines are for the two different hand groups, where the upper line represents the group that practiced with their right hand and the lower line the group that practiced with two hands.

The number of Fingers used had an influence on the reaction time, $F(2, 58)=135.62$, $p<.001$, $\eta_p^2=.82$, and that this also differed for using the right hand or using two hands F(2, 58)=9.95, p=.001, η_p^2=.26. Namely, for every number of fingers used, the right-handed group had higher reaction times. The difference in reaction time for using one finger was smaller between the right hand group and the two hand group, than for using two or three fingers. Furthermore, contrasts on the main effect of Fingers revealed that using two fingers has a significant higher reaction time than using one finger, F(1,29)=113.71, p<.001, η_p^2=.74, and using three fingers a significant higher reaction time than two, F(1,29)=84.02, p<.001, η_p^2=.85

There was no significant main effect on the two Chord Differences per one, two or three fingers F(1, 29)=6.51, p=.16, η_p^2=.18. This indicates that these different chords options did not result in different reaction times. These Chord Differences were just variations of a one, two or three key combination and should not have resulted in differences.

There was a difference in reaction times for the number of Fingers x Blocks, F(14, 406)=8.83, p<.001, η_p^2=.23, the reaction times decreased more over the blocks for the three and two fingers chords, than for the one finger response.

Practice phase errors

Overall, the right Hand Group had higher error rates than the group using two hands, F(1,29)=4.94, p=.03, η_p^2=.15. An overall mean of errors was calculated from the means per chord per blocks per participant for the group using two hands (M=1%, SD=1%) and the group using their right hand (M=2%, SD=2%),

For Block, the error rates decreased, F(7, 203)=6.39, p<.001, η_p^2=.18. Even though the right Hand Group had higher error rates, their rates decreased more over the Blocks, F(7, 203)=3.39, p=.01, η_p^2=.11. Additionally, a significant effect was found for the interaction between Chord Difference and Hand Group, F(1,29)=4.33, p=.046, η_p^2=.13.

A chord with three Fingers had higher error rates that when one or two Fingers were used, F(2,58)=18.69, p<.001, η_p^2=.39. When comparing this for the Hand Groups, there was a bigger difference between the one or two Fingers chords and the three Fingers chords for the right handed group than the group using two hands, F(2,58)=6.63, p=.01, η_p^2=.19. Lastly, the three Finger chords decreased over the Blocks, the two Finger chords decreases a little at the start and the one Finger response does not show much change, F(14,406)=3.58, p=.002, η_p^2=.11. This also differed for the Hand Groups, where there was overall a larger decrease for the right handed group per number of Fingers chords than for the group using two hands, F(14,406)=2.18, p=.04,η_p^2=.07.

Test phase RTs

For the Test phase RTs, a mixed ANOVA was executed with Hand Group as between subjects variable and number of Fingers (3), Familiar and Unfamiliar Chords (2), Hand Configuration (2) and Chord Difference (2) as factors.

Familiar Chords were performed significantly faster than Unfamiliar Chords, F(1, 28)= 14.64, p=.001,η_p^2=.34, meaning the reaction times differed based on if the chords were already practiced or not. Furthermore, in Figure 2 the reaction times can be seen for the two Hand Configurations with different lines for Familiar and Unfamiliar chords. It can be seen that Unfamiliar chords had higher reaction times both for the same and different Hand Configuration than for Familiar chords. Additionally, there is a greater difference between the different and same Hand Configuration for Familiar chords, than for Unfamiliar chords. The Familiar chords are performed faster with the same Hand Configuration than with the different Hand Configuration, which is also the case for the Unfamiliar chords. Thus, there was a significant interaction between Familiar versus Unfamiliar Chords and Hand Configuration, F(1, 28)=8.96, p=.01, η_p^2=.24.

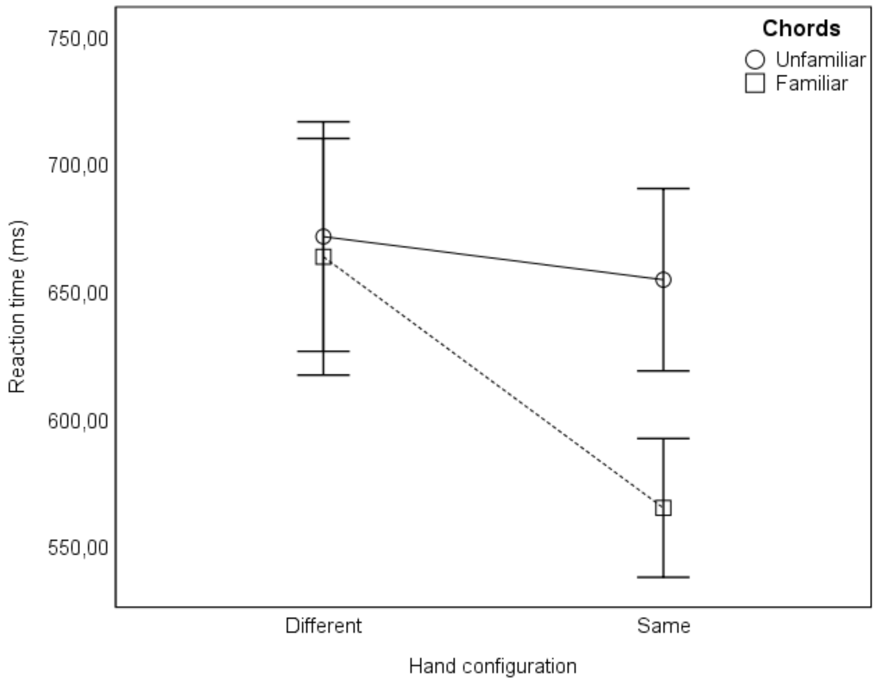

Figure 2 The reaction time in milliseconds for the two hand configuration with different lines for the familiar and unfamiliar chords. The two hand configurations could either be using two hands or using the right hand. "Different" means that the participant used the other hand configuration than what they used during the practice phases, and "Same" means they used the same hand configuration. Familiar chords are the 6 chords the participant practiced during the practice phase, and Unfamiliar chords are the 6 new chords.

When more Fingers were used to perform a chord, the reaction time also increased, F(1, 28)=202.36, p<.001,η_p^2=.88, which can also be seen in Figure 3. Contrast showed that there was a significant difference between chords with one and two Fingers, F(1,28)=208,93, p<.001, η_p^2=.88, and a significant difference between two and three Fingers, F(1,29)=120.76, p<.001, η_p^2=.81. Furthermore, the interaction effect between Fingers and Chord Difference was significant, F(2,56)=14.85, p<.001, η_p^2=.35, meaning that the different chords per one, two or three fingers also made a difference for the reaction times. With this, the main effect of Chord Difference was significant with F(1,28)=16.84, p<.001, η_p^2=.38.

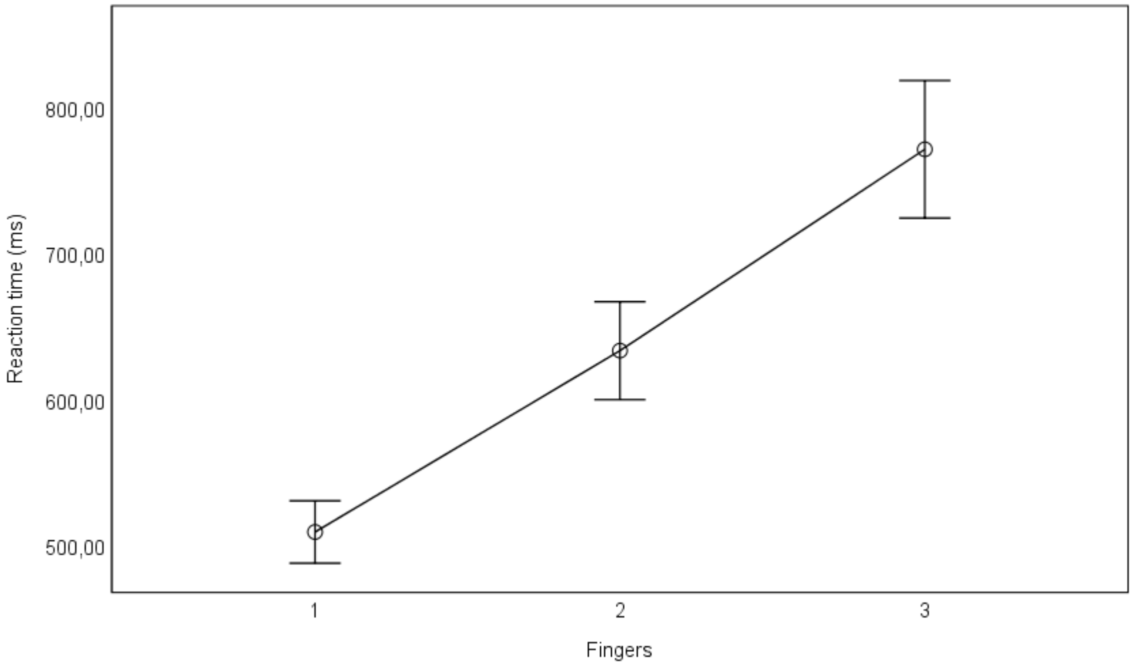

Figure 3 The reaction times in milliseconds, shown for the number of fingers that were used to perform a chord during the test phase. The two hand group either used their index and middle fingers, while the right hand group used their right index, middle, ring or little finger.

For Hand Configuration, the same configuration was performed faster, F(1,28)=20.12, p<.001,η_p^2=.42. But, the right Hand Group performed faster with the different Hand Configuration, and the Hand Group using two hands was faster with the same Hand Configuration, F(1,28)=43.73, p<.001,η_p^2=.61. For both Hand Configurations, it counts that more Fingers used to perform a chord meant a higher reaction time. For one and two Finger chords the reaction times were close, while for the three Finger chords there was a bigger difference between the same and different Hand Configuration, F(2, 56)=9.95, p=.001, η_p^2=.26. This also differed for the Hand Groups, where the RTs of the right Hand Group were close, for the group using two hands, the one Finger responses were close, there was a bigger difference between the two Hand Configuration conditions for the two Finger chords, and an even bigger difference for three Finger chords, $F(2,56)=19.91$, $p<.001$, $\eta_p^2=.42$.

Test phase errors

Less errors were made for Familiar Chords, $F(1,28)=5.57$, $p=.03$,$\eta_p^2=.17$. However, no other interactions with familiarity were significant.

For Hand Configuration, the same configuration yielded less errors than the different configuration $F(1,28)=5.52$, $p=.03$,$\eta_p^2=.17$. In interaction with Fingers, there was a bigger difference for the same and different Hand Configuration when three Finger chords were performed than when one or two finger chords were performed, $F(2,56)=9.23$ $p<.001$, $\eta_p^2=.25$. There was a significant difference in this for the two Hand Groups. For the group using two hands, during the same Hand Configuration similar error rates were present per number of Fingers. For the different Hand Configuration, more errors were made during the three Finger chords. For the right Hand Group, for the different Hand configuration there is a gradual increase from one finger chords to three finger chords. For the same Hand Configuration the scores are more similar, with two finger chords having a lower error rate, $F(2,56)=21.94$, $p<.001$, $\eta_p^2=.44$. The interaction effect between Hand Configuration x Chord Difference x Hand Group was significant with $F(1,28)=9.16$, $p=.01$,$\eta_p^2=.25$. Lastly, the interaction between Hand Configuration x Fingers x Chord Difference was also significant with $F(2,56)=3.96$, $\eta_p^2=.12$.

For Fingers, one and two finger chords had a lower error rate than the three finger chords, $F(2, 56)=16.95$, $p<.001$, $\eta_p^2=.38$. Furthermore, a significant interaction effect was found for Fingers and Chord Difference, $F(2,56)=6.43$, $p=.01$, $\eta_p^2=.19$.

Discussion

The current study focused on testing several hypotheses, of which the main one was if chord learning was even possible. This hypothesis is supported, there was a significant decrease in reaction time during the practice phases, showing participants got better at performing the learned chords. Secondly, it was expected that the learning curve would be different for the two hand groups. This hypothesis is rejected, there was no significant interaction between the Hand Group and Block and in Figure 1, a similar learning curve can be seen. However, there was a significant difference in reaction time between the two groups. This difference rejects the third hypothesis, that the right hand group would have lower reaction times than the two hand group. Namely, it is the other way round, where the two hand group performed significantly faster. Lastly, it was expected that there would be no transfer of chords to the other hand configuration during the test phase, which is supported by the results. The results show that for the familiar chords, a faster reaction time was achieved on the same hand configuration than on the different hand configuration. This seems to suggest that it is not the position of the keys that are learned, but the posture of the hand.

When comparing the faster reaction time for the two-handed group over the right-handed group with the second experiment from Hazeltine et al. (2007), a different result is found. In their study, they found that the group using two hands had a higher RT than the group using their left and the group using their right hand. They only used two element chords, whereas in the present study one, two and three element chords were performed. Additionally, it is not clearly stated with how many or which fingers their participants had to use to perform the chords, but it seems that they had to use all fingers of both hands in the bimanual hand condition (Hazeltine et al., 2007). While in the current study, in the bimanual condition only the two index and middle fingers were used. This difference could then be due to the biomechanical limitations of the fingers that are used, since the index finger can move more freely, while the ring and middle finger are influenced by the adjourning fingers (Van den Noort et al., 2016). Additionally, a study by Thon and Bonneviale (1995) also showed that unimanual or symmetric chords were performed faster than bimanual. Again, a difference with the current study is that they used all ten fingers to perform the chords. Furthermore, instead of groups per hand condition, their participants performed unimanual and bimanual chords mixed. Another difference lies in the presentation of the stimuli, since in their study a sketch was shown indicating how the fingers should be positioned (Thon & Bonneviale, 1995).

The last hypothesis about not being able to transfer chords to the other hand configuration is supported. Additionally, this seems to suggest that the learning is chord-specific instead of learning the positions of the keys. This is in line with the first two experiments from Hazeltine et al. (2007), where it was shown that new and reconfigured chords both had lower performances than the old, already learned chords. In a study by Verwey and Wright (2004), a discrete sequence production task was used to investigate different hand configurations and unfamiliar and familiar sequences. A sequence was performed with either three fingers of one hand, or two fingers from the left hand and one from the right. The experiment was spread over two days, with practice phases on the first day and fewer practice phases and a test phase on the second day. Their results showed that in the test phase the same hand configuration was faster than the different hand configuration for familiar chords. Furthermore, with the unpractised hand configuration unfamiliar sequences were performed slower than familiar sequences (Verwey & Wright, 2004). Even though their study is about sequence learning and spread over two days, it compares to the current study with the switching of hand configuration and looking at new and practiced responses. Similar to the current study is that the same hand configuration was faster than the different hand configuration for the familiar and unfamiliar responses.

Strengths and weaknesses

One of the limitations of this study has to do with the balance of the biomechanical limitations of the hand for the two different hand groups. The biomechanical limitations itself are not the problem, but that the different fingers that were used for the different hand condition may have caused a difference. Some participants said that they had trouble with either using their little or ring finger when pressing keys, which is also in line with the study from Van den Noort et al. (2016). Since the group using two hands did not have to use these fingers, this could have partially caused the lower reaction times for the right-handed group. Another limitation has to do with the duration and look of the program. In total, the experiment took almost three hours, with breaks included. Also, the program had a white background which caused that some participants noted that the screen seemed too bright. These two factors together caused that as the experiment went on, some participants found it hard to stay concentrated. During the test phase, the participants had to read the instructions carefully to read the correct hand configuration for the subblock. Since the experimenter could not read the screen or check afterwards if the participant used the correct hand configuration, this could have an influence on the results. Lastly, due to the decision to use only four fingers and four keys, the amount of possible chords is very limited.

A strong point of the current study is that, even though the duration of the experiment was long, at some point the reaction time and amount of errors stopped in quickly improving. This could indicate there was enough time to learn the given chords. Another strong point of the current study is that the chords are balanced, which can also be seen in Appendix A. Also, not a lot of research has been done on this topic even though our hands and fingers play an important role in our daily life. We use our hands and fingers daily for a wide range of tasks, so this study helps to understand how we learn.

Suggestions for further research and implications for practice

A suggestion for further research would be to change the chord design to balance the used fingers with regards to biomechanical limitations. This could either be using all fingers in the bimanual condition, or evening it out to have one index, middle, ring or little finger in both bimanual and unimanual condition. Another suggestion to build upon this research would be to look closer at the hand posture learning and if chords could be transferred. An idea for this would be to also include the left hand, and see if chords can be transferred from left to right, or right to left. During the practice phases, a few chords could be practiced with one of the hands and during the test phase the practiced chords will also be performed but with the other hand. In the test phase, the practiced chords could also be mirrored, so that the same fingers need to be used when playing with the other hand. Then a hypothesis would be if chords can be transferred to the other hand, and if mirrored chords are easier to transfer to the other hand condition.

The practical implications for the present study are in giving insights in differences between unimanual and bimanual learning. In turn, this can help in developing learning programs for example, playing a musical instrument.

Conclusion

Overall, it seems that chord learning is possible, with similar learning curves for both hand groups but the two handgroups did score differently. The reaction time might be different in this study due to the biomechanical limitations of the different fingers used. So while in this study the average reaction time for the group using their right hand only was higher than that of the group using two hands, this could be different if the same fingers were used in both conditions. Lastly, it seems that chord learning is chord-specific, since the unfamiliar chords performed during the test phase had a higher reaction time than familiar chords. The familiar chords were performed better with the same hand configuration than with the different hand configuration, seeming to suggest there is no transfer of chords.

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Appendix A: Table with Chord Design

Both tables show the key combinations that each participant had to press during the practice phase and test phase. For the hand groups, 1 means the right handed group and 2 the two handed group. The first letter before Chord, stands for either Left, Right or Both hands. The last letter or letters after the word Chord stand for the keys that were pressed on the keyboard, which could either be "C", "V", "B" or "N". The first row in the table is about the number of keys which were pressed, which could either be one, two or three.

PRACTICE Familiar

		1 key	1 key	2 keys	2 keys	3 keys	3 keys
						Left:1	Left:2
		Left	Right	1 hand	2 hands	Right:2	Right:1
Subject	**HandGroup**	**FCh1KL**	**FCh1KR**	**FCh2KH1**	**FCh2KH2**	**FCh3KL**	**FCh3KR**
1	1	LChordC	RChordB	L0ChordCV	B1ChordCB	LChordVBN	RChordCVN
2	2	LChordC	RChordB	L0ChordCV	B1ChordCB	LChordVBN	RChordCVN
3	1	LChordC	RChordB	L0ChordCV	**B2ChordCN**	LChordCBN	RChordCVN
4	2	LChordC	RChordB	L0ChordCV	**B2ChordCN**	LChordCBN	RChordCVN
5	1	LChordC	RChordN	R0ChordBN	B1chordVN	LChordCBN	RChordCVB
6	2	LChordC	RChordN	R0ChordBN	B1chordVN	LChordCBN	RChordCVB
7	1	LChordC	RChordN	R0ChordBN	B1ChordCB	LChordVBN	RChordCVB
8	2	LChordC	RChordN	R0ChordBN	B1ChordCB	LChordVBN	RChordCVB
9	1	LChordV	RChordB	L0ChordCV	**B2ChordCN**	LChordVBN	RChordCVB
10	2	LChordV	RChordB	L0ChordCV	**B2ChordCN**	LChordVBN	RChordCVB
11	1	LChordV	RChordB	L0ChordCV	B1chordVN	LChordCBN	RChordCVB
12	2	LChordV	RChordB	L0ChordCV	B1chordVN	LChordCBN	RChordCVB
13	1	LChordV	RChordN	R0ChordBN	B1ChordCB	LChordCBN	RChordCVN
14	2	LChordV	RChordN	R0ChordBN	B1ChordCB	LChordCBN	RChordCVN
15	1	LChordV	RChordN	R0ChordBN	**B2ChordCN**	LChordVBN	RChordCVN
16	2	LChordV	RChordN	R0ChordBN	**B2ChordCN**	LChordVBN	RChordCVN
17	1	LChordC	RChordB	R0ChordBN	B1chordVN	LChordVBN	RChordCVB
18	2	LChordC	RChordB	R0ChordBN	B1chordVN	LChordVBN	RChordCVB
19	1	LChordC	RChordB	R0ChordBN	B1ChordCB	LChordCBN	RChordCVB
20	2	LChordC	RChordB	R0ChordBN	B1ChordCB	LChordCBN	RChordCVB
21	1	LChordC	RChordN	L0ChordCV	**B2ChordCN**	LChordCBN	RChordCVN
22	2	LChordC	RChordN	L0ChordCV	**B2ChordCN**	LChordCBN	RChordCVN
23	1	LChordC	RChordN	L0ChordCV	B1chordVN	LChordVBN	RChordCVN
24	2	LChordC	RChordN	L0ChordCV	B1chordVN	LChordVBN	RChordCVN
25	1	LChordV	RChordB	R0ChordBN	B1ChordCB	LChordVBN	RChordCVN
26	2	LChordV	RChordB	R0ChordBN	B1ChordCB	LChordVBN	RChordCVN
27	1	LChordV	RChordB	R0ChordBN	**B2ChordCN**	LChordCBN	RChordCVN
28	2	LChordV	RChordB	R0ChordBN	**B2ChordCN**	LChordCBN	RChordCVN
29	1	LChordV	RChordN	L0ChordCV	B1chordVN	LChordCBN	RChordCVB
30	2	LChordV	RChordN	L0ChordCV	B1chordVN	LChordCBN	RChordCVB
31	1	LChordV	RChordN	L0ChordCV	B1ChordCB	LChordVBN	RChordCVB
32	2	LChordV	RChordN	L0ChordCV	B1ChordCB	LChordVBN	RChordCVB

TEST Unfamiliar

Subject	HandGroup	1 key Left **UCh1KL**	1 key Right **UCh1KR**	2 keys 1 hand **UCh2KH1**	2 keys 2 hands **UCh2KH2**	3 keys Left:1 Right:2 **UCh3KL**	3 keys Left:2 Right:1 **UCh3KR**
1	1+2	LChordV	RChordN	R0ChordBN	B1chordVN	LChordCBN	RChordCVB
2	1+2	LChordV	RChordN	R0ChordBN	B1chordVN	LChordCBN	RChordCVB
3	1+2	LChordV	RChordN	R0ChordBN	B1ChordCB	LChordVBN	RChordCVB
4	1+2	LChordV	RChordN	R0ChordBN	B1ChordCB	LChordVBN	RChordCVB
5	1+2	LChordV	RChordB	L0ChordCV	**B2ChordCN**	LChordVBN	RChordCVN
6	1+2	LChordV	RChordB	L0ChordCV	**B2ChordCN**	LChordVBN	RChordCVN
7	1+2	LChordV	RChordB	L0ChordCV	B1chordVN	LChordCBN	RChordCVN
8	1+2	LChordV	RChordB	L0ChordCV	B1chordVN	LChordCBN	RChordCVN
9	1+2	LChordC	RChordN	R0ChordBN	B1ChordCB	LChordCBN	RChordCVN
10	1+2	LChordC	RChordN	R0ChordBN	B1ChordCB	LChordCBN	RChordCVN
11	1+2	LChordC	RChordN	R0ChordBN	**B2ChordCN**	LChordVBN	RChordCVN
12	1+2	LChordC	RChordN	R0ChordBN	**B2ChordCN**	LChordVBN	RChordCVN
13	1+2	LChordC	RChordB	L0ChordCV	B1chordVN	LChordVBN	RChordCVB
14	1+2	LChordC	RChordB	L0ChordCV	B1chordVN	LChordVBN	RChordCVB
15	1+2	LChordC	RChordB	L0ChordCV	B1ChordCB	LChordCBN	RChordCVB
16	1+2	LChordC	RChordB	L0ChordCV	B1ChordCB	LChordCBN	RChordCVB
17	1+2	LChordV	RChordN	L0ChordCV	B1ChordCB	LChordCBN	RChordCVN
18	1+2	LChordV	RChordN	L0ChordCV	B1ChordCB	LChordCBN	RChordCVN
19	1+2	LChordV	RChordN	L0ChordCV	**B2ChordCN**	LChordVBN	RChordCVN
20	1+2	LChordV	RChordN	L0ChordCV	**B2ChordCN**	LChordVBN	RChordCVN
21	1+2	LChordV	RChordB	R0ChordBN	B1chordVN	LChordVBN	RChordCVB
22	1+2	LChordV	RChordB	R0ChordBN	B1chordVN	LChordVBN	RChordCVB
23	1+2	LChordV	RChordB	R0ChordBN	B1ChordCB	LChordCBN	RChordCVB
24	1+2	LChordV	RChordB	R0ChordBN	B1ChordCB	LChordCBN	RChordCVB
25	1+2	LChordC	RChordN	L0ChordCV	**B2ChordCN**	LChordCBN	RChordCVB
26	1+2	LChordC	RChordN	L0ChordCV	**B2ChordCN**	LChordCBN	RChordCVB
27	1+2	LChordC	RChordN	L0ChordCV	B1chordVN	LChordVBN	RChordCVB
28	1+2	LChordC	RChordN	L0ChordCV	B1chordVN	LChordVBN	RChordCVB
29	1+2	LChordC	RChordB	R0ChordBN	B1ChordCB	LChordVBN	RChordCVN
30	1+2	LChordC	RChordB	R0ChordBN	B1ChordCB	LChordVBN	RChordCVN
31	1+2	LChordC	RChordB	R0ChordBN	**B2ChordCN**	LChordCBN	RChordCVN
32	1+2	LChordC	RChordB	R0ChordBN	**B2ChordCN**	LChordCBN	RChordCVN