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Practice Effects and Transfer during Motor Skill Acquisition: a Chording Study

Bachelor Thesis

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Abstract

The present study investigated the mechanisms that allow for transfer of chord skill following unimanual practice. Chording refers to a muscle synergy in which a collective of keys is simultaneously pressed. It was hypothesised that with practice, a motoric effector-independent representation is developed (as opposed to a spatial representation) that encodes hand postures. As such, a behavioural reaction time experiment was conducted with a sample of 16 participants. During the practice phase, proficiency was attained with a set of 5 unimanual chords that were executed with either 2, 3 or 4 fingers. During the test phase, each participant executed in addition to the practise chords, mirror and novel chords with both the trained and untrained hand. The results suggest that neither a motoric (hand-posture) nor spatial effector-independent representation is developed that allows for transfer of practice effects. However, these findings are deemed inconclusive as statistical power was likely to be limited due to the highly variable sample. Lastly, a significant cost of reaction time for practised chords executed by the trained hand was observed upon introducing novel and mirror chords in the test phase. This suggests the presence of an effect that was not accounted for and may therefore have contributed to the lack of significant findings.

Practice Effects and Transfer during Motor Skill Acquisition: a Chording Study

The age-old adage goes 'practice makes perfect'. It demonstrates a fundamental principle that underlies every conceivable movement, spanning from basic tasks like grasping objects to the acquisition of complex motor skills. However, despite the outward simplicity that characterizes this relationship, the development of muscle synergies and their intricacies remains a debated topic today. An example of this involves *Chording*; the act of pressing a collective of keys simultaneously as can be seen whilst playing musical instruments (e.g. piano, saxophone).

Although a general consensus can be found in chord learning theory concerning the development of a representation encoding hand postures following practice (van den Bos, 2019; Hazeltine et al., 2007; Wifall et al., 2014), other aspects have received less attention and therefore warrant investigation. Namely, the phenomenon of unimanual transfer, the ability to transfer motor skills from the trained- to the untrained hand, has been observed in other motor learning experimental paradigms (e.g. motor sequence learning) but has yet to be touched upon in chord learning research. Such research suggests that next to a comparable hand-specific representation, additional motor- and cognitive representations may be learned that allow transfer of practice effects to the untrained limb (Bapi et al., 2000; Panzer et al., 2009; Verwey & Wright, 2004). Based on this perspective, the present research seeks to investigate the development of one such representation in the context of chord learning: a (non-spatial) effector-independent representation contingent on the specific fingers utilised in the execution of a chord and most likely involving a specific hand posture.

A recent theoretical account elucidating the mechanisms underlying motor skill learning is presented by Krakauer et al. (2019). This work defines motor learning as improvements of three components: formation of a movement goal, action selection and execution. These components may develop individually or in combination depending on the movement and context. Bearing this in mind, motor skill acquisition induces the development of representations at both a cognitive and motor level (Krakauer et al., 2019). Although not explicitly differentiating between the mentioned components, Seibel's study (1962) found evidence that chord skill is likely to be no exception to such improvement. In this study, a chording task was devised in which participants reacted to a set of 5 stimulus lights that were spatially mapped onto a keyboard with 5 keys. Performance was assessed in both error frequency and reaction time (RTs), which corresponded to the time it took for the combination of keys to be depressed after the stimuli was presented. The findings revealed that over the course of practice, RTs decreased without compromising the accuracy of execution, ultimately denoting skill acquisition (Seibel, 1962).

Chord Learning

Despite its early origins, the devised chording task by Seibel (1962) laid the groundwork for subsequent chording research and remains relevant in present times. One notable study conducted by

Hazeltine et al. (2007) employed the chord task to investigate *configural response learning*— the development of a response representation encoding coarticulate component movements (fingers in a chording posture). During their study, participants' performance on a set of practised chords was compared to two sets of unpractised chords. More specifically, *reconfigured* chords created by rearranging single component responses (fingers) from practised- into new configurations and *novel chords* that comprised a finger not used by any of the practised chords. Consistent findings emerged, indicating that both reconfigured and novel chords yielded diminished performance compared to the practised configurations. This suggests that chord skill acquisition happened through the development and use of representations encoding entire postures, rather than individual finger representations that are combined for execution (Hazeltine et al., 2007). In conclusion, following practice, a chord representation was developed in which associations between the component chord elements (fingers) were embedded, i.e. hand postures had been learned.

Related research investigated the effect of chord similarity by yet another adoption of the chording task. During their second experiment, Wifall et al. (2014) had participants undergo an 8-hour training regime in which a set of chords was learned. The chord sets differed within participants in terms of difficulty and between participants in terms of chord similarity. Chords were considered similar if they shared pairs of keypresses with other chords in the practice set. In addition to finding corroborating evidence concerning the aforementioned notion of hand posture learning, it was observed that interference arising from similar representations became more pronounced as they developed through practice. Consequently, performance seemed to decrease as inhibition of these was required to ensure accurate chord execution (Wifall et al., 2014). In short, following chord practice, the developed representations may interfere with one another as a product of similarity, ultimately impeding performance.

In a similar vein, recent findings in the domain of chord learning investigated the difference between unimanual and bimanual chord learning. In the practice phase of the study by van den Bos (2019), participants practised a set of chords exclusively with one or two hands, and it was found that, overall, bimanual chords yielded both lower response times and error rates in chord execution. Additionally, the study included a test phase where each participant executed that same set of practised chords in both the familiar- and unfamiliar configuration. Note that although different fingers were used when executing chords in the unfamiliar hand configuration, the spatial coordinates remained the same. Performance was found superior in the familiar configuration, ultimately suggesting that following practice, representations were developed that encoded the fingers used (hand postures) rather than the spatial coordinates of the chord keys (van den Bos, 2019). These findings were interpreted as evidence that intermanual transfer of chords may not be possible. However, given the study's experimental design, we believe that although the findings do not support the notion of a developed and used spatial representation, they do not account for alternative means of chord transfer (e.g. using mirrored chords). This is discussed in a later section.

Cross-domain Insights

Each of the aforementioned studies suggests that chord learning involves the development of hand posture representations. These studies do not, however, give a conclusive indication as to what type of information is embedded in these representations, and coincidingly do not adequately address the role of effector-dependency. Effector-dependency is the main focus of the present study as it addresses whether the information encoded is limb-specific or not. In light of the limited research on chord learning, we first turn to motor sequence theory for insights. The relevance of this may be questioned as chording involves the synchronous coarticulation of multiple effectors instead of a sequence of individual effectors. This is acknowledged, and the suggestions made by sequence learning theory are mainly used to identify theoretical possibilities for chord learning.

One study examining effector-dependency of motor sequence representations is Bapi et al. (2000). The findings of their study revealed that, over the course of practice, discrete effector-dependent and -independent representations are developed. Moreover, a temporal distinction between these two types of representations was observed, with effector-independent representations developing more rapidly during the initial stages of practice, thereby dominating execution. However, upon continuation of practice, the effector-dependent representations matured and gradually assumed greater control (also see Hikosaka et al., 1999; Verwey et al., 2014).

Panzer et al. (2009) expanded on this by investigating whether the type of movement performed in motor sequences determines which representation is used for execution, i.e. visuospatial or motoric. The authors believed that 'rapid' movement sequences may use different movement representations than 'slow' sequences as comparatively little time is available for on-line processing. As such, instead of sequences of key presses, flexor-extensor movements executed with the upper limb were used as these allowed for quicker execution. During the test phase of their study, transfer of sequencing skill was measured by executing mirrored (homologous muscle activation and joint angles) as well as visuospatial congruent sequences (sequences executed in the same spatial coordinates) using the unpractised limb. Performance was significantly better with the former, suggesting that the representation contributing to intermanual transfer of 'fast' sequences was motoric, rather than visuospatial (Panzer et al., 2009). In conclusion, evidence in the domain of motor sequence learning points towards the development of both effector-dependent and -independent representations following practice. Although addressing a different type of motor learning here, we postulate the possibility of similar representational development during chord learning. One that, considering the utilisation of motoric representations during 'fast' sequencing, encapsulates effector-independent motoric information.

Lastly, neurophysiological evidence may also support the notion of effector-independent learning of movements. A well-established principle holds that motor skill acquisition induces neuroplasticity in the brain (Adkins et al., 2006). These changes are predominantly observed in the contralateral hemisphere, which governs the movements of the opposite side of the body; a phenomenon known as contralateral control. However, research indicates that such changes in the brain are not exclusive to the contralateral hemisphere. For instance, Dai et al. (2001) found, using neuroimaging, that during unilateral hand training, elevated motor cortex activity and excitability of corticospinal output projections were engendered in the ipsilateral hemisphere too. Notably, Ruddy and Carson (2013) stated that such changes in the brain ipsilaterally from the side of movement execution may allow for increased performance by the contralateral limb, and thereby serve as a neurophysiological rationale for unimanual transfer. Considering this, one could propose that during unimanual chord learning, cortical changes are elicited that enable transfer of practice effects to the unpractised limb, ultimately extending the benefits of skill acquisition beyond the initially practised hand.

Present Study

The aim of the conducted experiment was to investigate the nature of the representations that are developed during chord skill acquisition. More specifically, to determine whether there is development of effector-independent representations following chord practice that encode combinations of chord elements (postures) rather than the spatial coordinates of the motor movement. To achieve this, an adoption of the chording task by Seibel (1963) was utilised. Similar to the mentioned chording studies, participants were subjected to a practice phase in which proficiency with a set of 5 different unimanual chords was to be attained. In the test phase, in addition to the practice chords, the performance of mirrored and novel chords was measured when executed with the trained and untrained hand. This was done to test the effector-dependency of the developed movement representations following practice.

The series of experiments conducted by Hazeltine et al. (2007) and Wifall et al. (2014) demonstrated that by practising chords, a representation is developed in which the hand posture is encoded. However, other than the findings by van den Bos (2019) that suggest that said representation is unlikely to be effector-independent and spatial, no conclusive indication can be found in the literature concerning the effector-dependency of said representations. Although concerning a different type of motor learning, motor sequence theory provides relevant insights in this context. Namely, evidence suggests that following practice, discrete effector-independent spatial and motoric representations develop that allow for transfer of the sequencing skill (Bapi et al., 2002; Panzer et al., 2009). Based on these findings, and considering the evidence of bilateral cortical plasticity during unimanual practice presented by Ruddy and Carson (2013), we postulated that following practice, an effector-independent representation encoding hand postures is developed that allows for the unimanual transfer of the chord skill. As such, it is expected that mirrored chords executed with the opposite hand are performed better than novel chords. To reiterate, mirrored chords executed by the opposite hand use the same fingers (i.e. hand posture) as practice chords. Furthermore, assuming that we find transfer to said mirrored chords, in order to ascertain that a motoric rather than a mirrored spatial representation is used for execution, mirrored chords with the practised hand were also executed. The absence of a difference between these and novel chords would confirm this aspect. Lastly, considering the study by van den Bos (2019) that found no evidence for a developed spatial representation used for chord execution, we expect to find similar performance for practice and novel chords when executed by the untrained hand. This would indicate the absence of a used spatial representation as the mentioned practised chords are executed in spatial coordinates similar to those in practice.

Methods

Participants

The study included a sample of 16 individuals who were recruited from the Behavioural, Management and Social sciences (BMS) test subject pool of the University of Twente. Dissemination of and registration to the study was done by means of the online Sona system. The sample consisted of healthy young adults aged 18 to 23 years (M=20.63, SD=1.63). Out of the 16 participants, 5 were male and 11 were female. Inclusion criteria required participants to have no professional or expert experience with piano/string instruments, as well as no regular engagement in playing video games. Additionally, participants were required to abstain from alcohol consumption for 24 hours prior to the study and identify themselves as non-smokers. As an incentive for participation, 3.5 points were awarded in the Sona system upon completion of the experiment.

Materials

The experiments were conducted at the BMS lab of the University of Twente. In order to limit distraction throughout, the room was soundproof with a partially covered window (¾) to let in natural light. Inside, an Optiplex 7050 desktop computer (Dell Technologies Inc., Round Rock, TX, USA) connected to a 16:9 aspect ratio, 24-inch monitor with a refresh rate of 75hz (LG Electronics Inc, Seoul, South Korea) was present on which the experiment was performed. In order to record button presses, a Razer Huntsman Tenkeyless N-Rollover (Razer Inc., Irvine, CA, USA) keyboard was utilised with the backlight switched off. For the participants' comfort and to minimise the risk of wrist strain, a keyboard wrist pad was provided, although its use was not mandatory (all participants opted for use). Lastly, a ceiling-mounted camera was present to monitor the participants.

Task

The experiment was executed using E-Prime® (Version 2.0.10.3562) software and contained 8 blocks of chording. The practice phase consisted of the first 7 blocks. Each practice block was split into two segments by means of a 30-second break. Moreover, in between successive blocks, an additional break of 4 minutes was provided. Each block consisted of 160 chord trials. Participants were given a unique set of 5 chords, which were repeated 32 times in a randomised order within each cycle. Thus, each individual chord was practised a total of 224 times during the practice phase. Block 8 concluded the test block. Within the test block, 2 new sets of chords were introduced: mirrored versions of practised chords (homologous finger use for chord execution by the other hand), and a set of 5 completely novel chords. All chords were consequently executed with both the trained and untrained hand, but grouped by hand in two individual segments within the block. Each set of chords was repeated 8 times, amounting to a total of 120 chord trials per hand. Lastly, note that the novel and mirrored chords performed by one participant in the test phase were the practice chords for another participant.

During the practice phase, 5 participant-specific chords were practised: two 2-finger, two 3-finger, and one 4-finger chord(s). Within the chord pairs, one was executed with the left, and one with the right limb, but never the same. The chords were prompted by placeholder fillings displayed on the monitor and corresponded to the input on the keyboard. As for the execution of the chords, all fingers could be utilised depending on the administered participant-specific set of chords. See Appendix A for the chord-design table. The left-hand chords used the buttons "A", "S", "D", "F", and "Space Bar" whereas chords for the right-hand used the buttons "H", "J", "K", "L", and "Space Bar". The "A" key was response-mapped to the left fifth digit finger, "S" mapped to the left ring finger and each finger followed suit until the thumb was placed on the "Space Bar". This was mirrored with the right hand, where the thumb was on the "Space Bar" and the fifth digit finger on the "L" key.

The stimuli were presented for a total of 2500 ms during which the chord was to be executed. When this period was over, depending on the input, feedback was provided both in text and in grey placeholder fillings that corresponded to the input. A 'timing-error' was displayed when the lag time between first and last keypress exceeded the threshold of 80ms. This was introduced to ensure valid chord execution (simultaneous pressing of keys). The 'miss' message was triggered under one of two conditions: firstly, when one or more input keys were absent, and secondly, in the event of a triggered 'false' message that arose when incorrect key input was detected, consequently highlighting the missed correct keys. In cases where input yielded one of these 3 types of negative feedback, chords were to be repeated until executed correctly. Overall, this feedback display lasted 1000 ms after which a non-ageing intertrial interval ensued (300-2500ms), i.e., a semi-random interval length where shorter intervals are more frequent than longer intervals (see Gottsdanker et al., 1986). Lastly, during both the 30-s and 4-min breaks, the mean reaction time and number of errors were displayed to the participants.

After the completion of Block 7, an awareness questionnaire was required to be filled out. Within this questionnaire, inquiry was made towards general demographic data (e.g. age, sex), whether they satisfied the exclusion criteria, and more importantly, chord awareness. Awareness of the practised chords was tested by asking participants to write down the individual chord combinations. In addition, participants had to indicate the strategy they utilised for remembering the chords by picking between 5 specified options: ‘I remembered the combination of the letters’, ‘I remembered the positions of the keys’, ‘I remembered the positions of the squares on the screen’, ‘I pressed the keys in my mind’, ‘I pressed the keys on the tabletop’ or by writing down their own (multiple answers were allowed).

Procedure

Upon arrival, participants were escorted to the designated experimental room. Prior to the onset of the experiment, participants were orally queried about their alcohol usage and smoking behaviour. Relevant instructions and information were provided both orally and in writing. Participants were also requested to complete an informed consent form and given the opportunity to ask questions. Lastly, participants were told not to use their phones at any point during the experiment. The experiment commenced with the researcher starting the computer program in front of participants, entering the participant and block number on the screen, and consequently, leaving the participant alone in the room. During the scheduled 4-min breaks, participants were allowed to sit back, leave the room to move, chat with the researcher or use the restroom.

After each break, the researcher manually restarted the experiment with the appropriate block number. Throughout the course of the experiment, this protocol was followed with no deviations except for the completion of the mentioned awareness questionnaire after Block 7. Upon completion of Block 8, a ‘thank you’ message was displayed for a brief period after which the program automatically closed, thereby marking the end of the experiment. The researcher returned, briefed the participants about the experiment's objective, use of data, and provided an opportunity to ask questions.

Data Analysis

Chord performance was measured in reaction time (ms) and accuracy. The mean reaction time was calculated per block for each participant. Note that only the RTs associated with correctly executed chords were retained. Two separate analyses on RTs were conducted. In order to evaluate chord learning during the practice phase, a mixed analysis of variance (ANOVA) was performed with mean chord RT as the dependent variable. The factors that were included were two within-subject variables, Block (7) and ChordKeys (3), and one between-subject variable called HandGroupPractice (2). The factor Block had seven levels pertaining to the practice block number (1-7). Factor ChordKeys referred to the number of fingers utilised to execute a specific chord: 2, 3 or 4 fingers. Lastly, HandGroupPractice was added as control and determined with what hand the 4-finger chord was executed. This was required as only one 4-finger chord was present in the chord set. The two levels corresponded to either the left or right hand.

To determine whether an effector-independent hand posture representation developed during practice, a similar mixed ANOVA was performed on the test phase RTs (Block 8). The model included three within-subject variables, ChordType (3), HandConfiguration (2), ChordKeys(3) and one between-subject variable called HandGroupPractice (2). The factors ChordKeys and HandGroupPractice were identical to the practice phase. Factor ChordType referred to three types of chords that were executed: practised, mirrored or novel. HandConfiguration was used as a factor to identify the hand that was executing chords. In the Trained condition, participants performed novel and practise chords using the same hand as during practice and mirror chords with the opposite hand. Conversely, in the Untrained condition, novel and practised chords were executed with the opposite hand as during practice, while the mirrored chords were executed with the same hand as during practice. Two identical analyses were performed on errors. In order to stabilise the variance, error proportions were arcsine-transformed before analysis (p. 356 in Winer et al. 1991). Lastly, a Mauchly's test of sphericity was performed, and when found significant, the corresponding *p* values were submitted to a Greenhouse-Geisser correction.

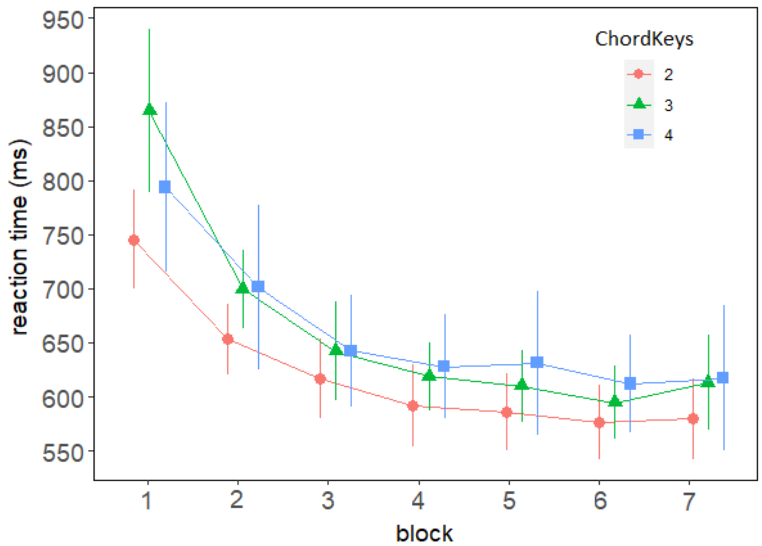
Results

Practise Phase RTs

To evaluate chord learning over practice, RTs were analysed using a 7 (Block) x 3 (ChordKeys: 2, 3 or 4 keys) x 2 (HandGroupPractice: left vs. right) mixed repeated-measures ANOVA. Figure 1 displays the relationship between mean reaction time and block, with different lines corresponding to the number of fingers required for chord execution. A significant main effect of Block was observed, $F(6,84) = 31.3$, $p < .001$, $\eta_p^2 = .69$, indicating that reaction time improved over the course of practice. The number of fingers used did not have a significant main effect $F(2, 28) = 1.1$, $p > .20$. The interaction of Block x ChordKeys was however significant, $F(12,168) = 3.6$, $p < .001$, $\eta_p^2 = .20$. Meaning, the effect of the number of fingers used to execute a chord differed among the training blocks.

Figure 1

Mean trial reaction time (RT) performance in milliseconds in practice blocks 1-7



Note. Error bars represent 95% confidence intervals.

Practice Phase Errors

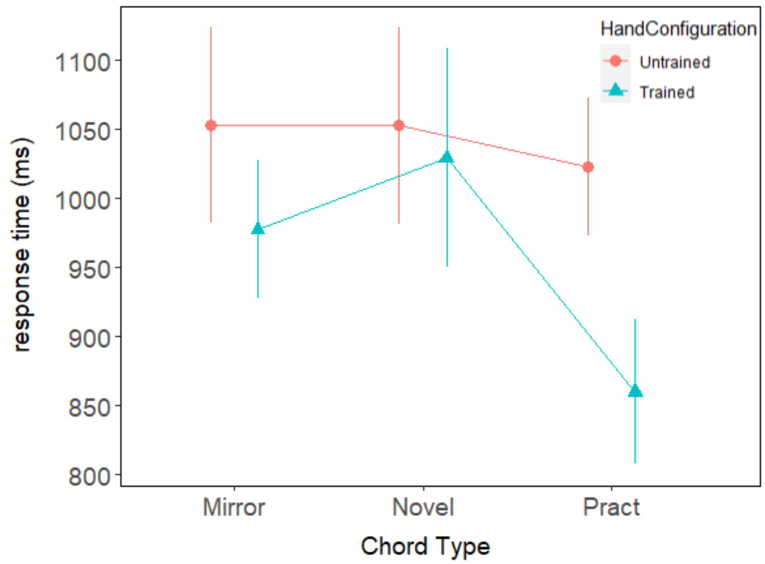
Overall proportion incorrect was calculated from the mean error proportions over the practice phase per participant (M=9%, SD=11%). A similar 7 x 3 x 2 ANOVA to that on RTs was performed on arcsine transformed error proportions. There was a significant effect of Block, $F(6,84) = 14.6$, $p < .001$, $\eta_p^2 = .51$, indicating that accuracy increased over the course of practice. The mean error percentage across all participants reduced from 17% in Block 1 to 8% in Block 7. ChordKeys was not found to influence error proportion (although marginally significant), $F(2,28) = 2.8$, $p = .094$, $\eta_p^2 = .17$. No interactions were found.

Test Phase RTs

In order to evaluate performance in the test phase, RTs were subjected to a 2 (HandConfiguration: Trained vs. Untrained) x 3 (ChordType: Practise vs. Novel vs. Mirror) x 3 (ChordKeys: 2, 3 or 4 keys) x 2 (HandGroupPractice: left vs. right) mixed repeated ANOVA. To reiterate, in the Trained configuration, practice and novel chords were executed with the same hand as during practice whilst the mirror chord was executed with the opposite hand, vice versa. A significant main effect of ChordType was found, $F(2,28) = 4.4$, $p = .038$, $\eta_p^2 = .24$. This means that reaction time varied as a product of what type of chord was being executed. In addition, a significant main effect of HandConfiguration was also observed, $F(1,14) = 8.4$, $p = 0.012$, $\eta_p^2 = .38$ indicating that reaction time also differed based on which hand was used to perform the chords. Figure 2 displays the performance in mean RTs for the individual chord types for each hand configuration. A significant interaction is observed between HandConfiguration and ChordType, $F(2,28) = 6.8$, $p = .012$, $\eta_p^2 = .32$ but not between ChordType and ChordKeys, $F(4,56) = 1$, $p = 0.371$.

Figure 2

Mean reaction time (RT) performance in milliseconds for each chord type during the test phase



Note. Error bars represent 95% confidence intervals.

Judging from Figure 2, chords executed in the Untrained configuration were performed slower across all chord types as opposed to the Trained configuration. Contrast analyses showed significant differences within the separate levels of HandConfiguration. Namely, in the Trained condition, the difference between mirror and practice chords was found significant, $F(1,14) = 26.9$, $p < .001$, $\eta_p^2 = .66$, indicating that practice chords executed with the same hand as during practise were performed better than mirrored chords executed by the opposite hand. In addition, although a difference between the mirror and novel chords can be seen, analysis shows this to be non-significant, $F(1,14) = 1.4$, $p > .20$. As for the Untrained configuration, no discernable discrepancy in the execution of novel and mirrored chords was observed. This indicates that mirror chords executed by the same hand as during practice displayed a level of novelty similar to that of actual novel chords. Some transfer can be seen for practice chords but analyses showed this to be non-significant (compared to novel chords), $F(1,14) = 0.5$, $p > .20$.

Lastly, the number of fingers required for chord execution (ChordKeys) was found to have a significant effect on RT, $F(2,28) = 34.2$, $p < .001$, $\eta_p^2 = .71$. Thus, reaction time differed depending on the amount of fingers used to execute a chord. No difference was observed for 3- and 4-key chords. However, 2-key chords were found to perform significantly faster than both 3- and 4-key chords, $F(1,14) = 56.4$, $p < 0.001$, $\eta_p^2 = .43$ and $F(1,14) = 47.5$, $p < .001$, $\eta_p^2 = .77$ respectively. No interaction was found between Chordkeys and HandConfiguration.

Test Phase Errors

Arcsine transformed error proportions were submitted to a 3 x 3 x 3 x 2 ANOVA, similar to that used with RTs. A significant effect of ChordType was found, $F(2,28) = 6.1$, $p = .015$, $\eta_p^2 = .30$ indicating that proportion errors differed among the chord types that were executed. The mean error rate for mirror, novel and practice chords amounted to 21%, 24% and 16% respectively. Contrast analyses showed an insignificant effect between mirror and novel chords, $F(1,14) = 1.3$, $p > .20$ but practice chords were found to be performed more accurately than both mirror chords $F(1,14) = 9.8$, $p = .007$, $\eta_p^2 = .41$, and novel chords $F(1,14) = 12.2$, $p = .004$, $\eta_p^2 = .47$. No interaction with factor HandConfiguration was found (although marginally significant), $F(2,28) = 3.0$, $p = 0.063$, $\eta_p^2 = .07$ indicating that the effect of ChordType was not dependent on what hand was used.

In addition, a significant main effect of ChordKeys was found, indicating that the proportion of errors differed as a product of how many keys were required to execute a chord, $F(2,28) = 19.3$, $p < .001$, $\eta_p^2 = .58$. The error rate for 2-, 3-, 4-key chords concluded 13%, 25%, 23% respectively. More specifically, although the proportions did not differ significantly between 3- and 4-finger chords, $F(1,14) = 2.5$, $p = .134$, $\eta_p^2 = .15$, 2-key chords were performed more accurately than both 3- and 4-key chords, $F(1,14) = 38.3$, $p < .001$ and $F(1,14) = 17.8$, $p < .001$ respectively. No interactions were found.

Discussion

The present study aimed to investigate the role of effector-dependency in the developed representations following chord practice. More specifically, to delineate the type of information embedded in the representations that allow for unimanual transfer of the chord skill, i.e. spatial or motoric. As such, performance in RT and error proportions of participants were compared between a set of practice, novel and mirrored chords. The main hypothesis predicted that through practice, an effector-independent representation encoding hand postures would develop that allows for the transfer of practice effects to the untrained limb. Given that no significant performance difference between novel and mirror chords executed with the opposite hand as during practice was found, this hypothesis can be rejected. Furthermore, the test controlling for the usage of a mirrored spatial representation also turned out to be non-significant. Conversely, the second hypothesis stated that chord skill would not transfer to the other hand utilising a spatial representation. This was confirmed as the performance of practice and novel chords executed with the opposite hand as during practice did not differ significantly.

Detached from context, the findings suggest that unimanual transfer of the chord skill may not be possible. Although the overall interaction of ChordType and ChordConfiguration was significant, individual contrasts were not. However, despite the absence of significant evidence indicating unimanual transfer for neither motoric nor spatially congruent chords executed by the opposite hand as during practice, some indications of transfer were observed. Referring to Figure 2, mirror chords yielded lower reaction times than novel chords in the Trained configuration. Conversely, the difference between novel and mirror chords in the Untrained configuration is comparably much smaller, indicating that if a significant effect was observed, this would not have been due to the usage of a mirrored spatial representation. Notably, upon closer examination of the used sample, a large variability between participants is observed, resulting in substantial ranges within the confidence intervals. Considering this, the results are deemed inconclusive regarding the transfer of chord skill using motoric representations, as the lack of significant effects may be attributed to limited statistical power (see limitations). Regrettably, the present findings do not offer a means to resolve this ambiguity.

As for transfer to the other hand by means of a spatial representation, more conclusive evidence is found. Specifically, in the Untrained configuration, both practice and novel chords yielded similar performance, indicating that participants experienced no benefits when executing chords in the practiced spatial coordinates. These results align with those by van den Bos (2019), which investigated the use of a spatial representation by having participants perform the practice chords in the test phase both uni- and bimanually, whilst having practiced the chord set with only one. Although the present findings employ a different means of assessing transfer using a spatial representation, namely the execution of the practice chords by the untrained hand, the gathered evidence supports the same conclusion; no spatial representation was utilised for chord execution following practice. Additionally, those same findings may also be interpreted as evidence supporting a hand posture learning mechanism. Previous findings that corroborate said mechanism did not account for chords in which a spatial representation was mirrored in the same hand (van den Bos, 2019; Hazeltine et al., 2007; Wifall et al., 2014). Considering this, the absence of evidence supporting the use of spatial representations, coupled with the observed performance advantage of practice- over novel chords in the Trained configuration, further substantiates the notion of a hand posture learning mechanism.

Interestingly, a significant cost in RT is observed for practice chords between the last practice block and the test block (~257ms). It seems that by having introduced novel and mirror chords to the test phase, the performance of practice chords diminished. Such an effect was also observed in each of the experiments by Hazeltine et al. (2007). The authors of the study concluded that the observed cost was not due to a methodological difference (increased number of repetitions in the practice trials). Instead, they hypothesised that it may have been due to a change in strategy by the participants following the introduction of novel chords. For instance, a more conservative approach to all chords as novel chords require such for successful execution (Hazeltine et al., 2007).

Although possible, we posit that it could also have been caused by the fewer available cognitive resources compared to the practice phase. Assuming that the novel chords have not had the opportunity to establish representations that could interfere with the practice chords as a product of similarity (see Wifall et al. 2014), the overall cognitive workload may still have increased due to the sheer increase in the number of chords to be executed. In reference to Cognitive Load Theory (Sweller, 2011), cognitive load may have increased due to the processing of the newly introduced chords, increasing overall task complexity (intrinsic load). By reason, such a load would result in fewer resources available for the initial set of 5 chords, potentially impeding performance. Therefore, future research may wish to investigate why a decrease in performance was observed upon entering the test phase and control for this in their own experiments. Perhaps by including separate blocks for mirror, novel and practice chords, one may be able to control for cognitive overload or a strategy change utilised for execution.

As mentioned, research concerning the intricacies of chord skill acquisition has received relatively little attention compared to other motor learning domains. Hence, cross-domain findings of motor sequence learning were discussed to identify theoretical possibilities for chord learning theory. Moreover, it remains unclear what specific processes may or may not be shared between the two. The study of Panzer et al. (2009) offered a tempting theoretical bridge used for insights between chord and sequence learning theory due to its usage of 'fast' sequences compared to previous studies (see Bapi et al., 2000). Instead of using key presses, flexor extensor movements by the upper limb were used as these allowed for overall quicker execution. Furthermore, the findings of Panzer (2009) were comparable to those of van den Bos (2019), as both indicated that a spatial representation may not be used by the opposite limb following practice (albeit in different motor learning paradigms). However, despite having increased similarity with the chord skill from a temporal perspective, additional differences from an effector-used perspective were introduced. Considering this, the present absence of transfer either indicates that the findings by Panzer et al. (2009) may not accurately reflect skill acquisition with hand movements, or serve as evidence indicating disparate processes between sequence and chord learning.

Strengths and Weaknesses

As mentioned, the main limitation of the present study concludes the questionable statistical power that may have contributed to the observed insignificant effects. Given that a large variability was observed between participants in the sample, we hypothesise that the used sample size may have been problematic. Indeed, a number of studies investigating the underlying representations of hand-motor skills opt for one that is larger than 16 participants (van den Bos, 2019; Kleine & Verwey 2009; Verwey et al. 2015). Considering this, future studies would be wise to do so as well.

However, other means of reducing variability among participants and thereby increasing statistical power are worth considering. One relevant limitation may have been the unengaging nature of the study which could have decreased cognitive function (see Eastwood et al., 2012 for review). The experiment lasted on average 2 hours and 45 minutes where, excluding the test phase, a limited set of chords was learned. Notably, the majority of participants reported experiencing fatigue and concentration difficulties at diverging points during the experiment, attributing them to the monotonous nature of the task. When the test phase ensued, however, heightened levels of concentration were necessary due to the introduction of additional chords. It is plausible that cognitive fatigue exerted an influence on the consequently obtained results, albeit varying among individual participants. In light of this, future research may benefit from exploring more engaging approaches to sustain participants' attentiveness throughout the entirety of the experiment. One way of achieving this may be the display of more elaborate feedback on participants' performance in between the trials of the practise phase. Although the mean reaction time and errors were given at the end of each individual practice block, a more elaborate display of this feedback in reference to previous blocks, through e.g. a learning curve, may be able to engage the participants more in the learning process (see Hatti and Timperley, 2007). After all, an increase of circa 50-100ms is hardly noticeable to the human participant, but is meaningful when taking into consideration one's overall improvement over the practice phase.

Worthy of mention are some strong points of the used experimental design. First, chords were balanced among participants to make sure that the observed effects were not specific to certain chords but representative for chording in general (Appendix A). Second, chord complexity was also balanced between participants to account for biomechanical and neural limitations that may arise during chord execution (Appendix A). Research has shown that fingers may not move independently from each other, a phenomenon coined 'enslaving' (Zatsiorsky et al., 2000; also see van den Noort et al., 2016). In reference to chord skill, depending on what fingers were used to execute a specific chord, more or less inhibition of adjacent fingers was required to ensure correct chord execution. This inhibition would have ultimately increased reaction time for specific chords, but not others. In addition, finger flexibility engendered by chord practice may also have allowed for quicker execution. To account for this, both hands were used to execute the chord sets. Lastly, referring to Figure 1, it can be seen that over practice, improvement decreased nearing asymptotic performance. This means that although the mentioned experimental design may have limited participants' cognitive ability, chords were successfully learned.

Conclusion

Taking the findings together, the present study found no evidence for a motoric representation allowing for transfer of the chord skill. Although lower reaction times for mirror chords executed by the untrained hand, as compared to novel chords, were found, this difference was insignificant. We postulate that consequent research is likely to find different results when accounting for the issues raised concerning statistical power. Conversely, more conclusive evidence was found for the absence of a used spatial representation that allows for unimanual transfer. Neither chords using spatial congruent versions of the initially practiced chords were found to be performed better than novel chords. Although the present study focuses on chord learning specifically, the findings of the present study and others in the chord learning domain are likely to be representative for more than just the chord skill. Taken in isolation, the act of executing a chord concludes the synchronous articulation of effectors which can also be seen in a variety of other hand movements that are frequently used (e.g. grasping).

References

Adkins, D. L., Boychuk, J., Remple, M. S., & Kleim, J. A. (2006). Motor training induces experience-specific patterns of plasticity across motor cortex and spinal cord. *Journal of Applied Physiology*, *101*(6), 1776–1782. https://doi.org/10.1152/japplphysiol.00515.2006

Bapi, R. S., Doya, K., & Harner, A. M. (2000). Evidence for effector independent and dependent representations and their differential time course of acquisition during motor sequence learning. *Experimental Brain Research*, *132*(2), 149–162. https://doi.org/10.1007/s002219900332

Dai, T., Liu, J., Sahgal, V., Brown, R., & Yue, G. (2001). Relationship between muscle output and functional MRI-measured brain activation. *Experimental Brain Research*, *140*(3), 290–300. https://doi.org/10.1007/s002210100815

Eastwood, J. D., Frischen, A., Fenske, M. J., & Smilek, D. (2012). The unengaged mind: Defining boredom in terms of attention. *Perspectives on Psychological Science*, *7*(5), 482–495. https://doi.org/10.1177/1745691612456044

Gottsdanker, R., Perkins, T., & Aftab, J. (1986). Studying reaction time with nonaging intervals: An effective procedure. *Behavior Research Methods, Instruments, & Computers*, *18*(3), 287–292. https://doi.org/10.3758/bf03204401

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of Educational Research*, *77*(1), 81–112. https://doi.org/10.3102/003465430298487

Hazeltine, E., Aparicio, P., Weinstein, A., & Ivry, R. B. (2007). Configural response learning: The acquisition of a nonpredictive motor skill. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(6), 1451–1467. https://doi.org/10.1037/0096-1523.33.6.1451

Kleine, E., & Verwey, W. B. (2008). Representations underlying skill in the discrete sequence production task: effect of hand used and hand position. *Psychological Research Psychologische Forschung*, *73*(5), 685–694. https://doi.org/10.1007/s00426-008-0174-2

Panzer, S., Krueger, M., Muehlbauer, T., Kovacs, A. J., & Shea, C. H. (2009). Inter-manual transfer and practice: Coding of simple motor sequences. *Acta Psychologica*, *131*(2), 99–109. https://doi.org/10.1016/j.actpsy.2009.03.004

Ruddy, K. L., & Carson, R. G. (2013). Neural pathways mediating cross education of motor function. *Frontiers in Human Neuroscience*, *7*. https://doi.org/10.3389/fnhum.2013.00397

Seibel, R. (1962). Performance on a five-finger chord keyboard. *Journal of Applied Psychology*, *46*(3), 165–169. https://doi.org/10.1037/h0047948

Sweller, J. (2011). Cognitive Load Theory. *Psychology of Learning and Motivation*, *55*(55), 37–76. https://doi.org/10.1016/b978-0-12-387691-1.00002-8 van den Bos, M. A. (2019). *Investigating a motor skill: The case of chording* [BSc Thesis]. http://essay.utwente.nl/78399/1/vandenBos_BA_BMS.pdf

van den Noort, J. C., van Beek, N., van der Kraan, T., Veeger, D. H. E. J., 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

Verwey, W. B., Groen, E. C., & Wright, D. L. (2015). The stuff that motor chunks are made of: Spatial instead of motor representations? *Experimental Brain Research*, *234*(2), 353–366. https://doi.org/10.1007/s00221-015-4457-8

Verwey, W. B., Shea, C. H., & Wright, D. L. (2014). 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., & Wright, D. L. (2004). Effector-independent and effector-dependent learning in the discrete sequence production task. *Psychological Research*, *68*(1), 64–70. https://doi.org/10.1007/s00426-003-0144-7

Wifall, T., McMurray, B., & Hazeltine, E. (2014). Perceptual similarity affects the learning curve (but not necessarily learning). *Journal of Experimental Psychology: General*, *143*(1), 312–331. https://doi.org/10.1037/a0030865

Winer, B. J., Brown, D. R., & Michels, K. M. (1991). *Statistical Principles in Experimental Design*. McGraw-Hill Humanities, Social Sciences & World Languages.

Zatsiorsky, V. M., Li, Z.-M., & Latash, M. L. (2000). Enslaving effects in multi-finger force production. *Experimental Brain Research*, *131*(2), 187–195. https://doi.org/10.1007/s002219900261

Appendix A

Chord Design Table with Chord Complexity

The tables illustrate the practice, mirror and novel chord sets that participants had to execute on a QWERTY keyboard throughout the experiment. Practice chords were performed both in the practice and test phase. Mirror and Novel chords were performed only in the test phase. The column 'Group' refers to the hand with which the 4-key chord was executed. The column 'chord' refers to the chord that was executed, in which the letter referred to what hand was used, and the number to which fingers were used. The column 'CCI' referred to chord complexity with 2 being the lowest and 6 the highest. Concerning the test phase, the three tables below correspond to the group of Trained of factor ChordConfiguration. For the group Untrained, the hand used for execution is switched to the opposing hand. Therefore, chord 'L12' by the Trained hand configuration corresponds to 'R12' by the Untrained. Note that ChordConfiguration is a within-subject variable as each participant executed the chord with both configurations during the test phase.

Chord Finger Allocation					
Number	1	2	3	4	5
Keys	SPACE	H	J	K	L
Right Hand	Thumb	index	middle	ring	pinky
Keys	A	S	D	F	SPACE
Left Hand	Pinky	Ring	Middle	Index	Thumb

PRACTISE		2-KEY				3-KEY				4-KEY	
Participant	Group	chord	CCI (low)	chord	CCI (high)	chord	CCI (low)	chord	CCI (high)	chord	CCI
1	LR	L12	2	R35	6	L123	2	R235	2	L1234	2
2	LR	L45	2	R13	6	L345	2	R134	2	L1345	4
3	RL	R23	4	L14	6	R145	4	L124	4	R2345	2
4	RL	R34	4	L25	6	R125	4	L245	4	R1235	4
5	LR	L12	2	R35	6	L123	2	R235	2	L1234	2
6	LR	L45	2	R13	6	L345	2	R134	2	L1345	4
7	RL	R23	4	L14	6	R145	4	L124	4	R2345	2
8	RL	R34	4	L25	6	R125	4	L245	4	R1235	4
9	RL	R12	2	L35	6	R123	2	L235	2	R1234	2
10	RL	R45	2	L13	6	R345	2	L134	2	R1345	4
11	LR	L23	4	R14	6	L145	4	R124	4	L2345	2
12	LR	L34	4	R25	6	L125	4	R245	4	L1235	4
13	RL	R12	2	L35	6	R123	2	L235	2	R1234	2
14	RL	R45	2	L13	6	R345	2	L134	2	R1345	4
15	LR	L23	4	R14	6	L145	4	R124	4	L2345	2
16	LR	L34	4	R25	6	L125	4	R245	4	L1235	4

MIRROR		2-KEY				3-KEY				4-KEY	
Participant	Group	chord	CCI (low)	chord	CCI (high)	chord	CCI (low)	chord	CCI (high)	chord	CCI
1	LR	R45	2	L13	6	R345	2	L134	6	R2345	2
2	LR	R12	2	L35	6	R123	2	L235	6	R1235	4
3	RL	L34	4	R25	6	L125	4	R245	6	L1234	2
4	RL	L23	4	R14	6	L145	4	R124	6	L1345	4
5	LR	R45	2	L13	6	R345	2	L134	6	R2345	2
6	LR	R12	2	L35	6	R123	2	L235	6	R1235	4
7	RL	L34	4	R25	6	L125	4	R245	6	L1234	2
8	RL	L23	4	R14	6	L145	4	R124	6	L1345	4
9	RL	L45	2	R13	6	L345	2	R134	6	L2345	2
10	RL	L12	2	R35	6	L123	2	R235	6	L1235	4
11	LR	R34	4	L25	6	R125	4	L245	6	R1234	2
12	LR	R23	4	L14	6	R145	4	L124	6	R1345	4
13	RL	L45	2	R13	6	L345	2	R134	6	L2345	2
14	RL	L12	2	R35	6	L123	2	R235	6	L1235	4
15	LR	R34	4	L25	6	R125	4	L245	6	R1234	2
16	LR	R23	4	L14	6	R145	4	L124	6	R1345	4

NEW		2-KEY				3-KEY				4-KEY	
Participant	Group	chord	CCI (low)	chord	CCI (high)	chord	CCI (low)	chord	CCI (high)	chord	CCI
1	LR	L23	4	R14	6	L145	4	R124	6	L1235	4
2	LR	L34	4	R25	6	L125	4	R245	6	R2345	2
3	RL	R12	2	L35	6	R123	2	L235	6	L1345	4
4	RL	R45	2	L13	6	R345	2	L134	6	R1234	2
5	LR	L23	4	R14	6	L145	4	R124	6	R1235	4
6	LR	L34	4	R25	6	L125	4	R245	6	L2345	2
7	RL	R12	2	L35	6	R123	2	L235	6	R1345	4
8	RL	R45	2	L13	6	R345	2	L134	6	L1234	2
9	RL	R23	4	L14	6	R145	4	L124	6	R1345	4
10	RL	R34	4	L25	6	R125	4	L245	6	L2345	2
11	LR	L12	2	R35	6	L123	2	R235	6	R1345	4
12	LR	L45	2	R13	6	L345	2	R134	6	L1234	2
13	RL	R23	4	L14	6	R145	4	L124	6	R1235	4
14	RL	R34	4	L25	6	R125	4	L245	6	L2345	2
15	LR	L12	2	R35	6	L123	2	R235	6	R1345	4
16	LR	L45	2	R13	6	L345	2	R134	6	L1234	2