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Human performance characteristics of three-finger chord sequences

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Abstract

This study addressed human performance characteristics of chord sequences using a framework where each alphabetic letter is represented by a unit of three three-finger chords recalled according to a mnemonic. Fourteen participants conducted the chording task during four one-hour sessions. First, sequences of related chords formed temporal units were the inter-unit time (847 ms) was longer than the intra-unit time (117 ms). The hold times for the chords in a unit formed a distinct long-short-long rhythm (151 ms, 133 ms and 144 ms). The rate of errors was smallest for the first chord (27.1%) followed by the last chord (34.8%) and largest for the middle chord in a unit (38.1%). Practice manifested itself in significantly shorter inter-chord time and chord hold times. Chords were built and released in steps, where the time to add a finger, or release a finger, was related to the number of fingers already used. Moreover, it took longer to release a chord (25 ms) than to construct a chord (16 ms). The chord hold times were related to the Hamming distance between successive chords. Both the inter-chord times and the chord hold times were reduced through practice. Chord transitions with a Hamming distance of one resulted in most errors and chord transitions with two identical or complementary chords had the lowest error rate. Implications of these results are that chording speed may increase if frequent chord transitions are designed to have a small Hamming distances. Errors are reduced by designing chord alphabets such that frequent chord transition involving just one finger changes are avoided.

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Keywords: Human performance; Chording; Mobile HCI; Temporal keystroke dynamics; Key-pressing.

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1. Introduction

Chording is an input style used for text entry [1] with one hand [2, 3, 4, 5], two hands [2] or other variations [6, 7]. Chording is used for instantaneous transcription of speech [8] and by physically disabled users who are unable to use conventional QWERTY keyboards [9, 10].

Previous studies of chording have focused on speed and accuracy of isolated chords. For instance, Seibel [5] showed that the chord hold time and the error rates increase with the number of fingers used except when all the fingers are used simultaneously. Little is known about chord sequences and how the individual chords are constructed and released. However, there is a vast literature that addresses timing and accuracy aspects of key-pressing sequences [11].

First, it has been shown that humans separate key-press sequences into chunks, where the time between the key-presses separating the chunks is longer than the time between key-presses belonging to the same chunk [12]. Experiments suggest that these rhythmic patterns are caused by the development of integrated sequence representations also known as motor chunks [13]. There is also a minimum time between key-presses due to the biomechanical properties of the fingers [14].

Next, experiments have shown that the position within a chunk has an effect on the temporal dynamics of key-pressing. In an early typing study by Sternberg et al (described in [11]) it was found that the first key-press in a sequence was associated with the longest time and that the second key-press was associated with a much smaller time. In three key-press sequences the third key-press was longer than the second key-press (long-short-long). Finally, the error rates have been found to increase with the key-press position within a chunk, with a dip in error rate for the last key-press in the chunk [11].

The following terminology was introduced (see Fig. 1). *Chord hold time* was defined as the time from when the first keystroke of a chord was pressed to when the last key of that chord was released. The *inter-chord time* was defined as the time from when the last key of a chord was released to when the first key of the next chord was pressed. A *unit* was defined as a sequence of three related chords. The *inter-chord time* of chords within a unit was defined as the intra-unit time, and the *inter-chord time* separating the last chord of a unit and the first chord of the subsequent unit was termed *inter-unit time*. Next, the *chord construction time* was defined as the time from the first key-press of a chord to the start of the last key-press of a chord upon which the chord was completed. Similarly, the *chord release time* was defined as the time the first key of a chord was released to when all the keys of the chord were released.

This study is structured around the following hypotheses: *Hypothesis 1:* Chord sequences are temporally split into units where the inter-unit time is longer than the intra-unit time. *Hypothesis 2:* The hold time of chords within a unit are input in a rhythmic participant-independent pattern where the first chord is the longest, the second chord is the shortest and third chord is long. *Hypothesis 3:* The first chord in a unit will have the least errors, the errors increase with the chord position within the unit with a dip in error rate for the last chord in a unit. *Hypothesis 4:* Practice leads to shorter inter-chord time. *Hypothesis 5a:* The hold time of a chord is related to the Hamming distance to the previous chord in the sequence. *Hypothesis 6a:* The error rate of a chord is related to the Hamming distance to the previous chord in the sequence. *Hypothesis 5b:* The hold time is shorter for chords that are identical or complementary (zero or maximum Hamming distance) to the previous chord in the sequence compared to chord pairs that are partially different. *Hypothesis 6b:* The error rate is lower for chords that are identical or complementary (zero or maximum Hamming distance) to the previous chord in the sequence compared to chord pairs that are partially different. *Hypothesis 7:* The time to add a finger to a two finger chord is longer than the time to add a finger to a one-finger chord. Similarly, the time to release a finger from a three finger chord is longer than the time to release a finger from a two finger chord. *Hypothesis 8:* The time to construct a chord is shorter than the time to release a chord.

In order to test the above hypotheses a simple chording task was designed which was intended to appear meaningful and easy to learn. Instead of participants having to memorize lists of chording patterns, the chording task relies on participants learning a simple input principle that utilises spatial mnemonics (see Fig. 2). Symbols are entered as sequences of three-finger chords and the study is therefore limited to three-finger chords. The principle behind the chording task is as follows.

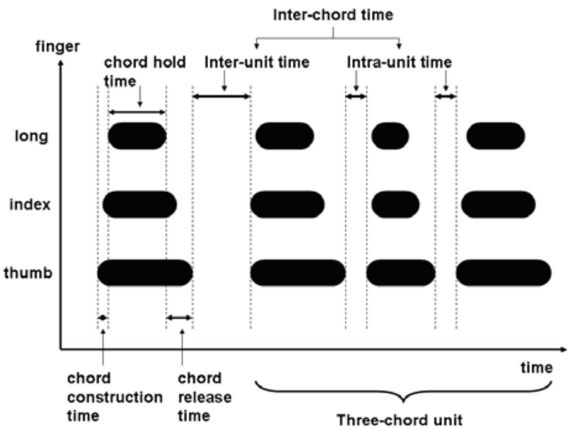

Fig. 1. Definition of terminology.

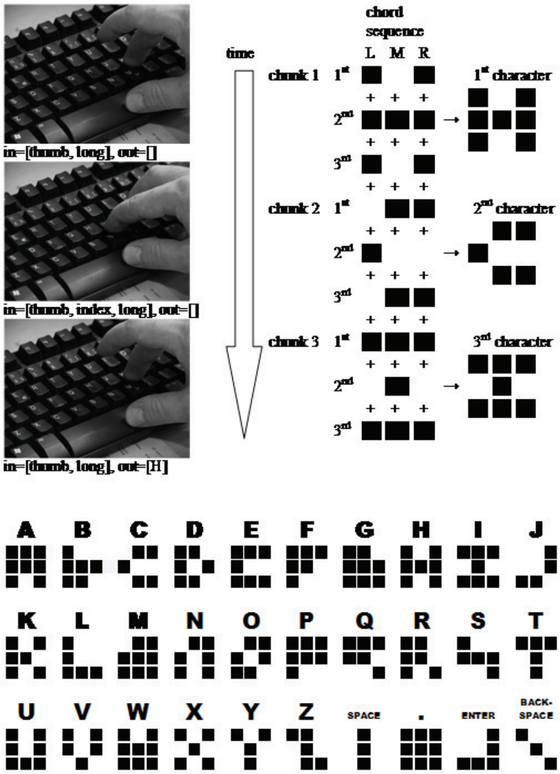

Fig. 2. Input mechanism and alphabet.

First, the participant visualises the character as a 3x3 grid of pixels. Then the participant inputs this character grid in three "horizontal" steps from top to bottom. In each step one chord is entered representing one scan-line of the character grid. For each chord, one, two or three keys are used simultaneously. After the three chords are entered, the required character is retrieved and the process is repeated. The three chord sequences allowed the chunking hypotheses to be tested.

2. Method

Fourteen students from the 2nd year, 3rd year and master-level computer science classes participated in the experiment. All participants were male and ranged in age from 21 to 38 years with a mean age of 26 years. All the participants were right-handed and were not suffering from visual impairment or dyslexia.

DELL Optiflex GX 270 computers with DELL 17" AS 501 LCD monitors, optical mice and full DELL QWERTY keyboards were used in the experiment. Two Java Applets running in a web browser were written for the purpose of the study. One applet contained the character pattern reference and was presented as a virtual QWERTY keyboard. By clicking on one of its keys a graphical representation of the corresponding 3x3 pixel map for the character was displayed for 1 second. The second applet was the text-entry application and has two areas. The top area showed a phrase to be copied and a multi-line text-entry area is provided at the bottom. As users entered text into the system the text is displayed in the text-entry area. The text scrolled automatically so that one can see a trail of previously entered phrases. The right side of the screen was used to display short instructions on how to operate the system. Both applets logged user activity to a local hard disk.

The applet was configured to accept keystrokes from the SPACE, J and K keys as these are the key positions that naturally fit the thumb, index finger and middle finger of the right hand. The SPACE, J and K keys were used as the left, middle and right chord-keys respectively. The character was displayed upon keying of the three consecutive chords. There was no feedback as the participant keyed in the two first chords of a character. A timeout mechanism was built-in such that if participants halted for more than 500 ms the system would reset the construction of the current character and the participants would have to re-enter the character. This mechanism allowed participants to redo a character by waiting for more than 500 ms.

All participants were given the same briefing on the tasks and the operating system. The principal investigator was present during the sessions to answer questions and provide help. Each session lasted one hour and each participant participated in four sessions. Each session was separated by approximately three days. No training session was provided.

Four different lists of phrases randomly selected from the phrase sets described in [15] were used. Each phrase list, with approximately equal characteristics, was used only once throughout the four sessions to eliminate phrase learning effects. All phrases were presented in lowercase as lowercase characters are easier to read, and the phrases did not contain special characters or punctuation symbols.

The users were asked to conduct a text copying task where the phrases were displayed one by one. Once completing a phrase, the user had to enter the chord sequences for ENTER to display the next phrase. No facility for going back was provided. Participants were instructed to correct errors using the chord sequences representing BACKSPACE.

The text-entry applet logged all the activity. Time measurements were based on medians for each participant over an entire session as medians are robust to outliers. Error percentages were based on means for each participant over one session and were computed from comparing the entered text to the source text, and identifying character sequences that contained BACKSPACE, which indicated that the participant had identified and corrected an erroneously entered character. For each erroneous character chord-level error statistics could be computed by comparing the three chords of each erroneous character with those of its corresponding correct character.

3. Results

3.1. Chord hold times

Chord hold times were analysed in within-subjects repeated measures ANOVAs with two within-subject parameters: session (1-4) and chord position within a unit (first, second or third). Practice had an effect on the median chord hold time ($F(3,143)=4.4; p<.005$). Hence, the median hold time was reduced with practice from 147.9 ms during the first session to 137.0 ms during the last session. Moreover, the position of a chord within a unit had an effect on the chord hold time ($F(2,143)=21.5; p<.001$). Fig. 3 shows the mean hold time of each of the three chords of a unit (character). The first chord in the sequence had the longest duration (151.2 ms), the last chord had the second longest duration (144.0 ms) and the middle chord had the shortest duration (133.2 ms). Post hoc-testing reveals that the hold time of the second chord was significantly different to both the first chord and third chord in the three chord sequences (Tukey HSD, $p <.001$) while the first and the third chords are not significantly different. No interaction between session and location of the chord in the sequence was observed ($F(6,143)=0.7; p>.66$).

3.2. Effects of chord position on errors

Errors were represented as the percentage error distribution for the three chord positions in a unit. Errors were analysed in within-subjects ANOVAs with two within-subject parameters: session (1-4) and chord position within a unit (first, second or third). Fig. 3 shows the distribution of chord errors in relation to position within a three-chord unit. Chord position within a unit had an effect on errors ($F(2,155)=34.6; p<.001$). Post-hoc tests revealed that the proportion of errors associated with the first chord (27.1%) was significantly lower than the proportion of errors associated with the second (38.2%) and third chord (34.7%) for a three-chord unit (Tukey HSD, $p<.001$) while the proportion of errors for the second and the third chords in the three chord sequences were not significantly different. Practice had no effect on error.

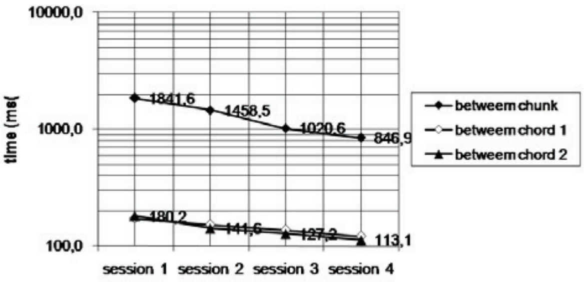

Fig. 4. A log-plot of the inter-chord time as a function of practice.

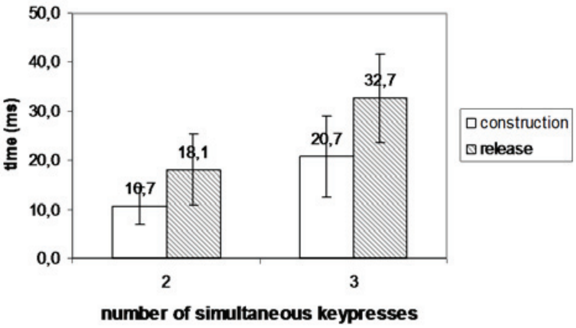

Fig. 5. Chord construction and release times.

Fig. 3 reveals a trade-off between speed and accuracy. When the chord hold time is the longest the error percentage is the lowest, when the chord hold time is medium the error percentage is medium and when the chord hold time is the shortest the error percentage is the highest.

3.3. Inter-chord time

Fig. 4 shows a log-plot of the inter-chord time as a function of practice. Inter-chord times were also analysed in within-subjects ANOVAs with two within-subject parameters: session (1-4) and chord position within a unit (first, second or third). Chord position had an effect on the inter-chord time ($F(2,143) = 125.5$; $p<.001$). Post-hoc testing revealed that the mean inter-unit time (1292. ms) were significantly different from the intra-unit time (Tukey HSD, $p<.001$) while the two durations between the three chords of a unit (145 ms / 141 ms) were not significantly different. Moreover, practice had also an effect on the inter-chord time ($F(3,143)=5.9$;$p<.001$)), and a significant interaction was found between practice and chord position ($F(6,143)=4.3$;$p<.001$).

3.4. Chord construction and release times

Chord construction and release times were analysed in within-subjects ANOVAs with three within-subject parameters: session (1-4), operation (construction and release) and number of fingers (2-3). The construction and release times are illustrated in Fig. 5.

Type of operation had an effect ($F(1,195)=134.6$;$p<.001$) as the mean time to release chords (25.4 ms) was nearly twice as long as the time to construct chords (15.7 ms). Moreover, the number of fingers had an effect on the time to construct and release chords ($F(1,195)=218.4$;$p<.001$) as the mean time to construct a three-finger chord (20.7 ms) was nearly twice as long as the time construct a two-finger chord (10.7 ms) and the time to release a three-finger chord (32.7 ms) was close twice as long as releasing a two-finger chord (18.1 ms). There was also an interaction between operation and number of fingers ($F(1,195)=7.7$;$p<.006$). Practice had no effect ($F(3,195)=1.4$;$p>.24$).

3.5. Effect of chord transition on hold time

Chord hold times were measured with respect to their Hamming distance to the previous chord in the sequence. Chord hold times were analysed in within-subjects ANOVAs with two within-subject parameters: session (1-4) and Hamming distance to the preceding chord (0-3). The effect of Hamming distance between consecutive chords was significant ($F(3,207)=37.4$;$p<.001$) and the chord hold time is therefore affected by the type of chord transition. Post-hoc tests revealed that all the hold times were significantly different apart from chord transitions involving a Hamming stance of 2 and 3. The times associated with chord transitions of varying Hamming distance are shown in Fig. 6. When the Hamming distance between two consecutive chords was zero, i.e., identical chords, the mean time was the shortest (110 ms). The mean time was larger for chord transitions involving larger Hamming distances, such as 131 ms with a Hamming distance of 1, and 156 ms with a Hamming distance of 2.

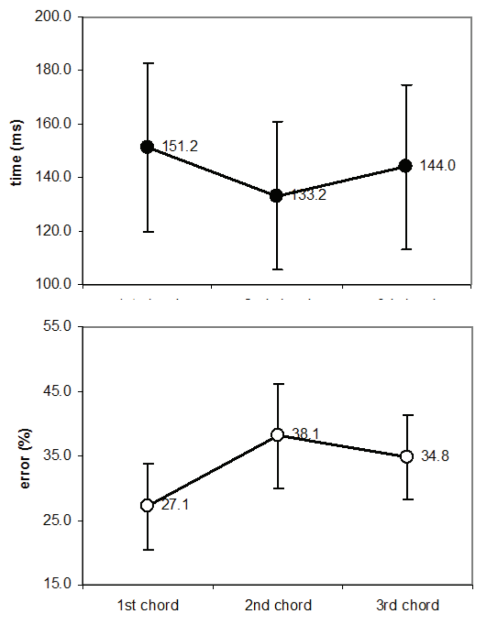

Fig. 3. The hold times and error percentages for the three chords in a unit. Error-bars show standard deviation.

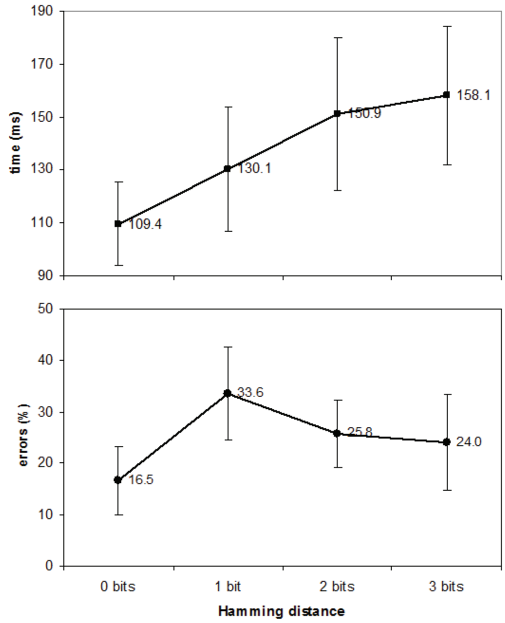

Fig. 6. The hold times and error percentages associated with chord transitions of varying Hamming distance. Error-bars show standard deviation.

The mean time was the longest (160 ms) for chord transitions with a Hamming distance of 3 representing two completely complementary chords. Practice had no effect (F(3,207)=0.9;p>.46).

3.6. Effect of chord transition on error

Errors were also represented as the percentage error distribution for chord transitions of varying Hamming distance. Errors were analysed in within-subjects ANOVAs with two within-subject parameters: session (1-4) and Hamming distance (1-4). The observations were scaled to remove bias as fewer chord transitions have Hamming distances of 0 and 3 than Hamming distances of 1 and 2. The Hamming distance between chords had a significant effect on errors (F(3,207)=40.8;p<.001). Post-hoc tests revealed that the error proportions associated with all the Hamming distances were significantly different apart from transitions involving a Hamming distance of 2 and 3, respectively. Fig. 6 shows the percentage of errors associated with different Hamming distances. Chord transitions with a Hamming distance of 0 were associated with the fewest errors (16.6%), chords with a Hamming distance of 1 were associated with most errors (33.5%) and chords with a Hamming distance of 2 and 3 were associated with 25.8% and 24.0% of the errors respectively. Practice had no effect on errors.

4. Discussion

The results show that temporal patterns emerged without any instructional influences during the trials. First, the intra-unit time (117 ms) was shorter than the inter-unit time (847 ms). Hypothesis 1, which predicts that sequences of related chords within units become temporally separated, was therefore supported by the results. Next, the chord hold times within units formed rhythmic long-short-long patterns (151 ms, 133 ms and 144 ms). Hypothesis 2 could therefore be accepted. One implication of hypotheses 1 and 2 is that the temporal characteristics of related chords can be used to segment chord sequences into units of related chords.

Moreover, the results support hypothesis 3 which suggest that related chords (within a unit) affect each other in terms of errors, since the two last chords of three-chord sequences had more errors than the first chord (27.1%), where the second chord had most errors (38.1%). The large quantities of errors for the middle chord in a sequence of three chords can be interpreted as follows. When starting the character by pressing the first chord, the time between the end of the previous chord and the start of the current chord may be sufficiently long for the subjects to be sufficiently prepared. But, when entering the second chord the participant has to make a transition from the finger position of the first chord to the second chord and the probability of errors is consequently higher. The same situation occurs when moving from the second chord to the third chord. Therefore, both the second and the third chords are associated with more errors than the first chord. Again, the second chord is associated with more errors than the third chord because it is immediately between two other chords. The third chord is only directly adjacent to the second chord, again assuming that the chord hold time is sufficiently large for the participant to prepare for the next unit of chords. Moreover, participants may plan the third chord while entering the second chord and hence be participant to additional cognitive load.

Moreover, Fig. 3 shows that there is a speed accuracy trade off. When the chord hold time is the shortest (133 ms) the error percentage is the largest (38.1%) and when the chord hold time is the longest (151 ms) the error percentage is the lowest (27.1%). A speed accuracy trade off explains the relationship between the observed chord hold time pattern and error percentage pattern.

Next, the results showed that the inter-chord time is reduced with practice (inter unit time from 1842 ms to 847 ms and intra unit time from 176 ms to 117ms) which confirm hypothesis 4. Moreover, the chord hold times were also significantly reduced through practice (from 151 ms to 144 ms), although the effect on inter-chord time was much stronger than the effect on chord hold times. Therefore, the median inter-chord time gives an indication of the participants' skill level. This is consistent with existing psychomotor research.

The chord hold time was related to the Hamming distance between two chords (ranging from 109 ms to 158 ms), and this observation confirms Hypothesis 5a. The large times associated with large Hamming distances were caused by the physical finger movements involved. A larger Hamming distance requires more fingers to be moved than two chords that have a small Hamming distance. Therefore, overall performance is maximized by designing chording alphabets such that frequent chord transitions have a small Hamming distance. Hypothesis 5b, which states that the chord hold times follows the event file model, was rejected based on the observations.

The error rate pattern was different to the hold time pattern. The low error percentage (16.5%) associated with chord sequences with a Hamming distance of 0 suggests that repeated chords results in the fewest errors. However, the second lowest percentage of errors (24.0%) was associated with Hamming distances of 3, suggesting that completely complementary chords, i.e., chord sequences where all fingers change up/down state results in fewer errors. Next, the large error percentage (33.6%) of chords with a Hamming distance of 1 suggests that partial chord transitions resulted in most errors. A Hamming distance of 1 means that only one finger in a chord has changed state from key-up to key-down or vice versa. Such chords transitions are therefore partial. Chord transitions with a Hamming distance of 2 (25.8% errors) can represent either two-finger partial chord transitions where one key is held while another key is released while a third is pressed, or a partial transition from a one-finger chord to a three-finger chord. A Hamming distance of 2 can also indicate a complementary chord transition where one key is released and another is pressed. These observations are consistent with the event-file effect, i.e., the difference caused by partial versus non-partial stimulus-response pairs was visible in terms of errors although not in chording hold times, as complementary chord transitions resulted in fewer errors than partial chord transitions. Therefore, hypothesis 6a was rejected, namely that the error rate is related to the Hamming distance between chords. Instead, the results support hypothesis 6b which states that the error rates are explained by the event file model, i.e., partial spatial tasks are associated with the largest error rates. One implication of this result is that errors can be minimized if chording alphabets are designed such that frequent chord transitions are complementary (maximum Hamming distance) or identical (minimum Hamming distance). Note that a trade-off exists between chord-hold times and error rates. Although both the error rates and hold times were minimal for repeated chord transitions, the error rates were large while chord-hold times were small for partial chord transitions. Similarly, complementary chords were associated with fewer errors but high chord-hold times.

Multiple-finger chords were constructed gradually as fingers were not pressed simultaneously. It took nearly twice as long to construct three-finger chords (21 ms) than two-finger chords (11 ms), and nearly twice as long to release three-finger chords (33 ms) than two-finger chords (18 ms). This observation confirmed hypothesis 7 which attributes the times of adding or removing fingers to or from existing chords to limited cognitive resources. Moreover, the release of a chord took nearly twice as long (25 ms) as its construction (16 ms), and this observation is predicted by hypothesis 8. A chord is virtually "hit" as it involves a rapid explosive-like downward motion followed by a slower retraction. Note that the chord construction and release times were unaffected by practice.

Finally, hypothesis 7 predicts Seibel's [5] observations of chord timing, namely that chords involving many fingers take longer than chords involving few fingers. Chords are constructed and released gradually. The time to add a finger to, or release a finger from, a chord is related to the number of fingers already in use.

5. Conclusions

This empirical study addressed the human performance characteristics of chord sequence input. Units of three chord sequences comprising one, two or three fingers were studied. The results suggest that several findings from the key-pressing literature also apply to chording. First, the results show that related chords were grouped into units that are separated by longer times (847 ms) than chords within a unit (117 ms). A distinct rhythmic pattern was observed for the units of three chords of the form long-short-long (151 ms, 133 ms and 144 ms). Both the time between the chords and the chord hold time were reduced with practice. Chord hold times were affected by the Hamming distance between successive chords, where the succession of two chords with a large Hamming distance took longer than two consecutive chords with a shorter Hamming distance (109 – 158 ms). Chords were constructed and released in steps where the chord release times were longer (25 ms) than the chord construction times (16 ms). The times associated with constructing (21 ms) and releasing (33 ms) three-finger chords were nearly twice as long as the time to construct (11 ms) and release (18 ms) two-finger chords. Next, more errors were associated with the middle chord (38.1%) in a three-chord sequence than the first (27.1%) and last chords (34.8%). The first chord had the fewest errors. Errors were also related to the Hamming distance between chord pairs. Identical chord pairs resulted in the fewest errors (16.1%), while partial chord transitions with a Hamming distance of 1 resulted in the most errors (33.6%). Chord transitions involving Hamming distances of 2 and 3 were associated with medium error rates (25.8% and 24.0%).

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