The Utility of a Technique for Testing the Difference in Ease of Chords on the Ternary Chord Keyboard

by

Thomas F. Callaghan

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Industrial Engineering and Operations Research

APPROVED:

K.H.E. Kroemer, Chairman

Robert J. Beaton

Dennis L. Price

September, 1989

Blacksburg, Virginia

The Utility of a Technique for Testing the Difference in Ease of Chords on the Ternary Chord Keyboard

by

Thomas F. Callaghan

K.H.E. Kroemer, Chairman

Industrial Engineering and Operations Research

(ABSTRACT)

In a pilot study, response times of 64 possible chords on the Ternary Chord Keyboard (TCK) were compared in order to establish a basis for assigning characters to chords. It was found that subjects had faster response times for some chords than others. Upon close inspection of the experimental procedure, it appeared that the way in which the chords were cued caused part of the differences in response time, which had been expected to depend only on chord motor differences.

The present study was designed to examine the hypotheses that chord cueing caused part of the differences in chord response times, and that this effect of cueing is consistent over practice; and also the hypotheses that the results of the pilot study reflected the motor (movement time) difference between chords, and that the difference itself is consistent over practice. This was done in the framework of Sternberg's Additive Factors Method.

It was found that the cueing scheme used in the pilot study did not cause the differences in chord response times. However, the differences in chord movement time was not reflected by the use of the pilot study paradigm. This technique should therefore not be used in ordering chords according to chord ease.

Acknowledgements

I would first like to thank my committee members, Dennis Price, and Robert Beaton, and especially my committee chairman, K.H.E. Kroemer, for their instruction and guidance. Thanks is also due to my fellow graduate students for their help and support, especially .

Finally, this thesis would not have been possible without the love, support, and caring of my family: my brothers , my sisters and ; and my parents , to whom this thesis is dedicated.

Table of Contents

List of Illustrations

List of Tables

Introduction

The Ternary Chord Keyboard

The Ternary Chord Keyboard (TCK) is a device that is used for computer input, much like a conventional "QWERTY" keyboard. (See Figures 1, 2 and 3.) However, the TCK has only eight keys. The keys are separated into two groups of four, one key for each finger on either hand. The fingers remain on the keys at all times. There are no keys for the thumbs.

Each key has three positions: aft, neutral, and fore. The dimensions of the keys and the keyboard are shown in Figures 4 and 5. Displacement of the key tops is 0.64 mm in either direction, and requires a force of 0.7 to 1.0 N.

Symbols are entered by changing the position (from neutral) of one key in each of the two four-key groups, concurrently using one finger from each hand. This combination of key displacements is called a chord. With this scheme, 64 different chords are possi-

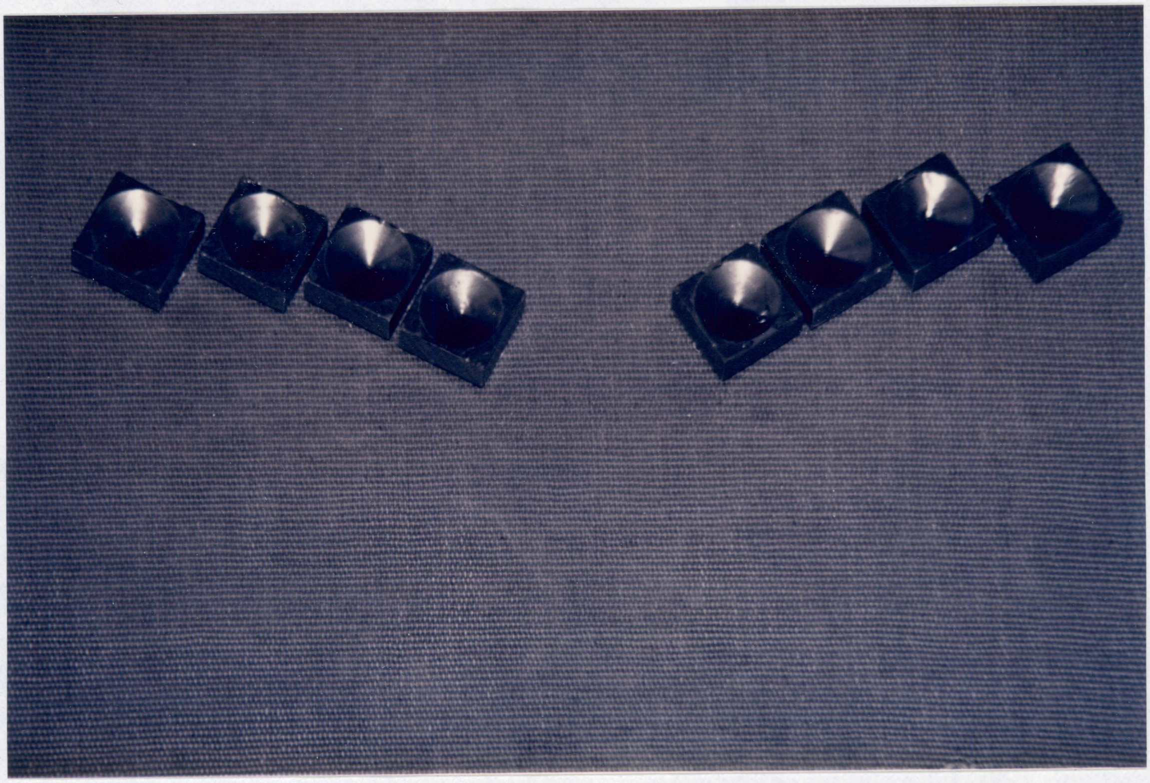


Figure 1. The Ternary Chord Keyboard: Top view.

Figure 2. The Ternary Chord Keyboard: Side view.

Figure 3. The Ternary Chord Keyboard: Subject at workstation.

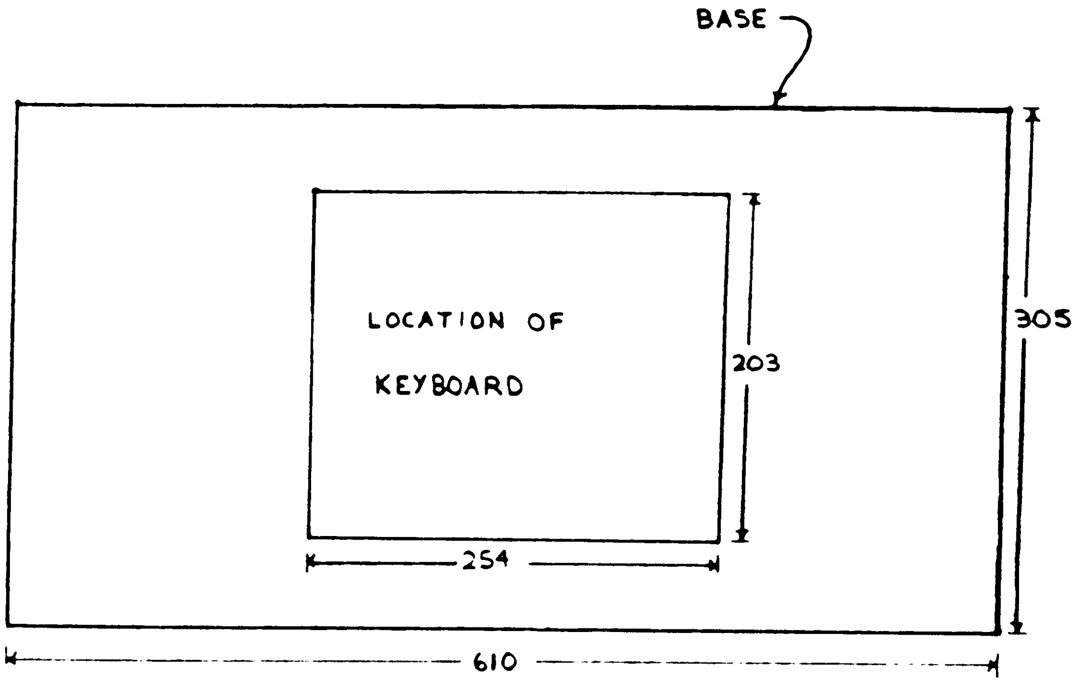


Figure 4. The Ternary Chord Keyboard: Dimensions (mm) of the base with the keyboard site.

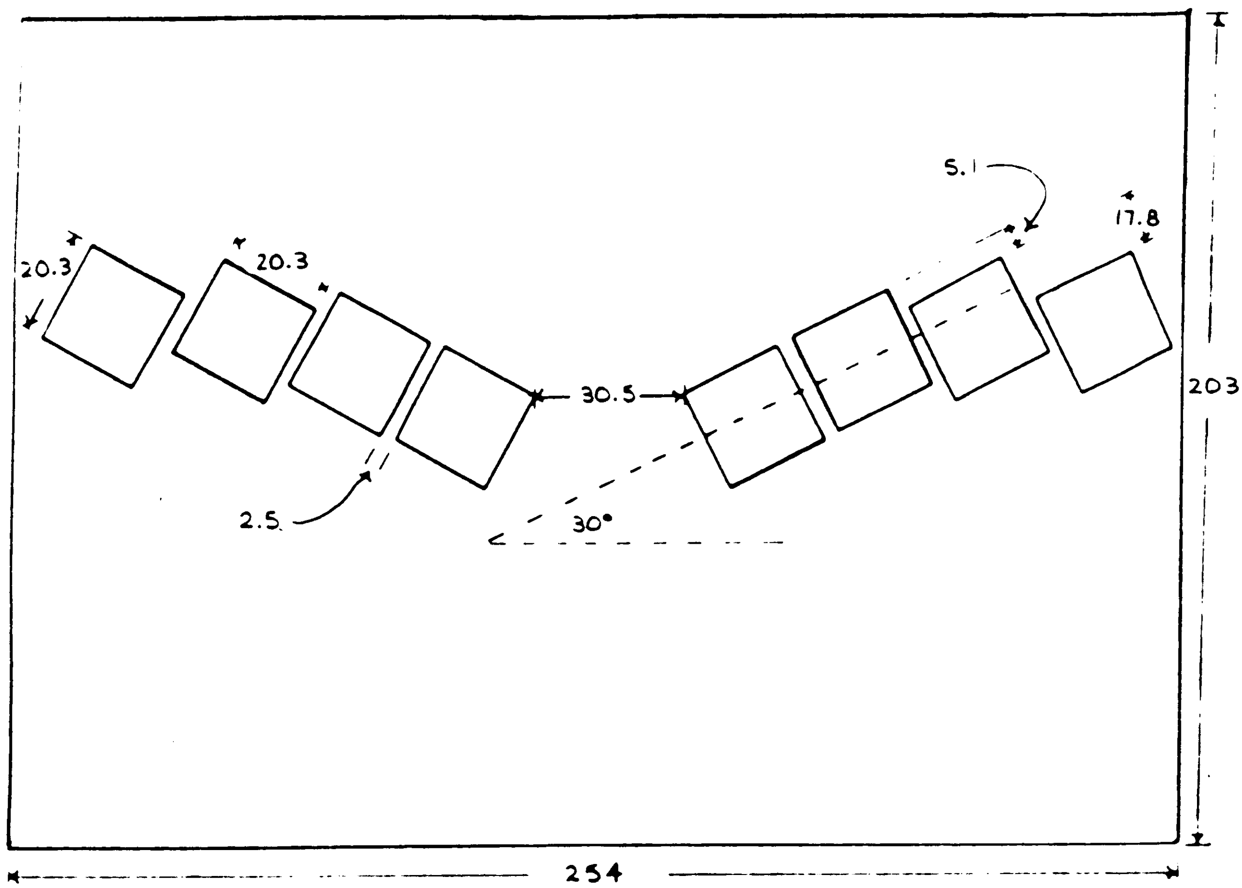


Figure 5. The Ternary Chord Keyboard: Key dimensions (mm).

ble. Different chords are assigned different characters. A method for conducting this assignment was the topic of a pilot study.

Pilot Study

The pilot study was conducted to begin the process of assigning characters to different chords on the TCK. The intention was to assign the chords which were executed the fastest to the characters which appeared most frequently in text. The first step was to establish an ordering of chords from fastest to slowest. Subjects were required to respond to a representation of each of the 64 different chords by executing the cued chord as accurately and quickly as possible. This visual representation, which fit into a visual angle of about 7-8 degrees, appeared on a computer screen in the form of 8 essentially horizontally arranged boxes, each of which represented one of the eight TCK keys. (See Figure 6, which is in the actual size of the representation.) An intended displacement of each key was indicated by an actual displacement and shading of the appropriate box on the CRT.

The pilot study revealed that there was a difference in chord response times.

When reviewing the results, the question arose as to what caused these differences in chord response time? Was it just the actual time it took to execute the chords, or was it also the way in which the chords were cued? If the cueing scheme did influence response time, this would confound the chord ease ordering, since the ordering measure is the time it takes to move the correct keys, not visual or mental processing time. While

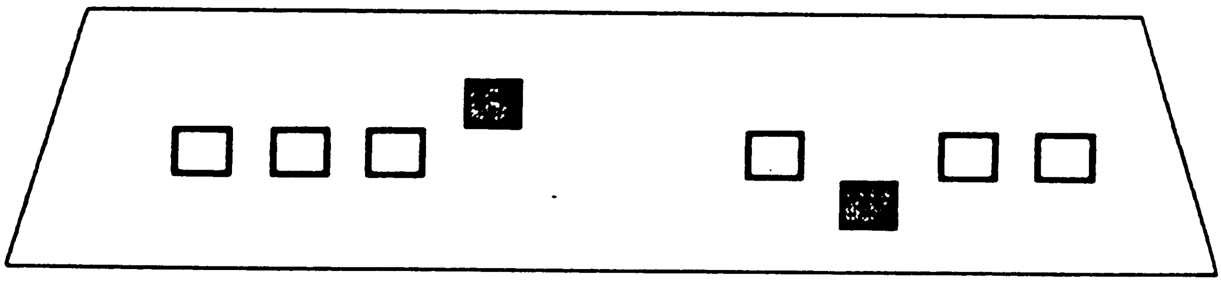


Figure 6. The cueing scheme used in the pilot study.

these times would naturally be included in response time, they should be the same for all chords.

There is evidence to suggest that the cueing scheme used could have influenced the response times of different chords unequally. Vickers (1979) describes a cueing scheme very similar to the one used in the pilot study. He used a line of eight horizontally arranged lights, separated into two groups of four by a center line. Each light represented one of eight keys, one key under each of the eight fingers (no thumb keys). He described discrimination of the lights on the two extreme ends of the line (the two little finger lights) and those on either side of the center line (the two index finger lights) as being quicker than the discrimination of the other lights. Also, Welford (1975) found that slower reactions involving the same cueing scheme were not associated with the (middle and ring) fingers used, but with the light positions that corresponded to them. Finally, Raji, Gopher, and Kimchi (1987) found that chords which involved keys located at natural anchor points (at the ends or next to the center line) were easier to identify. Thus, it is feasible that the cueing scheme used in the pilot study did affect response time differently for different chords.

Another question that arose was do the differences in movement time between the chords become less pronounced as a subject becomes more practiced, so that eventually it might be useless as a ordering measure? Seibel (1962b) found that while the most difficult chords on his chord keyboard showed the greatest reduction in response time as a function of practice, this reduction reached an asymptotic level. Further, he stated that "Practice does not overcome the differences in difficulty as measured by the average DRTs" (discrimination reaction times) (Seibel, 1962b, p.16). If this is true of the TCK chords, then the pursuit of ordering these chords according to movement time is worthwhile. However, if chords do not differ significantly after practice, ordering is not needed. The reason for this will become apparent in the *Chord-Character Assignment for the TCK* section of this paper.

Purpose

The present study sought to answer the following questions:

1. Was the cueing scheme responsible for part of the difference in chord response time, and if it was, does its effect on response time change significantly with practice?

2. Is the movement time difference between chords exposed by the technique used in the pilot study, and if so, does the difference change significantly with practice?

It is believed that these questions must be answered before a true ordering of the chords, and therefore an optimal chord-character assignment, can be done.

Literature Review

Background Information on Keyboards and the TCK

The keyboard is a primary device through which people input data to computers. Despite this fact, the keyboard layout most used today was designed in 1873 by C. Latham Sholes (Litterick, 1981). Over the past 126 years, attempts have been made to improve this layout. These attempts include an alphabetical arrangement of keys and the Dvorak layout, both of which attempt to improve typing performance. Such improved performance is questionable (Norman and Fisher, 1982; and Michales, 1971).

A relatively new attempt at improving keyboard input involves chord keyboards. With a chord keyboard, characters, and possibly whole words, are input by activating not one key but combinations of two or more keys. The history of chord keyboards dates back to 1942, when Achille Colombo requested a patent on a mechanical chord keyboard (Conrad and Longman, 1965). Since then numerous other chord keyboards have been proposed. They involve different numbers of keys, and some require the use of both hands while others require only one (Fathallah, 1988; Richardson, Telson, Koch, and Chrysler, 1987; Gopher, 1986; Bartram and Feggou, 1985; Bartram and Lee, 1985; Gopher, Karis, and Koenig, 1985; Gopher, Karis, Koenig, and Donchin, 1984; Amell, 1982; Noyes, 1983; Gopher and Eilam, 1979; Rochester, Bequaert, and Sharp, 1979; Sidorsky, 1974; Conrad and Longman, 1965; Cornog, Hockman, and Craig, 1963; Seibel, 1963, 1962b, 1962a; Ratz and Ritchie, 1961; Lockhead and Klemmer, 1959; and Klemmer, 1958).

Although these chord keyboards differ in many respects, all use binary keys of various designs which have only two states: off and on. The off state exists when a key is not pressed, while the on state exists when it is.

A new type of chord keyboard has been proposed by VATELL Corporation, Christiansburg, Virginia (U.S. Patent 4,775,255 of 9 September, 1988). This keyboard, called the Ternary Chord Keyboard (TCK), involves keys which have three states: two on and one off. The off state occurs when the key is in its neutral position, while the on states are produced by either pushing the key forward or pulling it backward from neutral. There are two advantages of ternary keys over binary keys. First, the fore-aft motion of fingers on this key is less straining than the up-down motions required for binary keys. Second, ternary keys offer an extra active state. The advantage of this can be seen in the fact that if a keyboard has eight keys, one for each finger (excluding the thumbs), the binary keyboard has only 256 possible chords, while the ternary keyboard has 6561 (Langley, 1988).

As stated before, the TCK has eight ternary keys, one for each finger. There are no keys for the thumbs, and the user's fingers remain on the keys at all times. From the 6561 possible chords, "the only key combinations which represent valid characters are those in which one finger of the right hand operates its key, and one finger of the left finger operates its key" (Langley, 1988, p.1). This decision by the patent holder is taken as a given for the research reported here.

Developing the TCK

In improving and developing the TCK, three main areas of research must be pursued: physical design, user training, and chord-character assignment. The physical design should take ergonomic considerations into account, such as those mentioned by Kroemer (1972), Nakaseko, Grandjean, Hunting, and Gierer (1985), and Alden, Daniels, and Kaharick (1972). Development of a training program should include a review of the training, learning and cognitive literature, as well as typing programs that already exist for other keyboard configurations (Glencross and Bluhm, 1986; and Baddeley and Longman, 1978, for example). The task of chord-character assignment is the topic of the present investigation.

Chord-Character Assignment for the TCK

Factors and Approaches

There have been different strategies for chord-character assignment. One such strategy involved capitalizing on users' visual imagery capabilities. Gopher and Eilam (1979) developed such an assignment strategy for a four-key typewriter. They assigned Hebrew letters to chords in which the keys used represented the shape of the letter. Likewise, with his "Alpha-Dot" system, Sidorsky (1974) tried to associate the shape of characters with the physical arrangement of the keys that were used to produce them. While this approach did meet with some success, especially on the Gopher and Eilam keyboard, both of these keyboards were one-handed, and involved the execution of more than one chord for some characters. Because of this, this approach does not seem appropriate for a two-handed keyboard such as the TCK.

Another chord-character assignment technique was used by Ratz and Ritchie (1961), Lockhead and Klemmer (1959), Klemmer (1958), and Cornog, Hockman, and Craig (1963). This technique involved assigning the most frequently occurring characters (or group of characters) to the easiest (quickest) chords.

Since many references exist which describe the frequency of characters in written text (Konheim, 1981, for example), and because one might want to use this keyboard for a task which involves characters other than those involved in normal text input, the bulk of the work involved in chord assignment is to decide which are the easiest chords. Once this is accomplished, a user can determine the frequency distribution of his/her characters, and assign them appropriately to chords.

Although they are not investigated further in this paper, other considerations might be made when assigning characters to TCK chords. First, the strength of the fingers, as measured by maximum pushing force, could be considered (Haaland, Winger, and Olson, 1963, cited in Alden et al., 1972; Barter, Frey, and Truett, 1956; and Armstrong, 1982), assigning the most frequently used characters to the chords involving the strongest fingers. Second, characters which belong to certain distinct groups, such as numbers and punctuation marks, could be assigned to chords which have some characteristic (a finger?) in common. Also, characters that appear together often, such as "Q" and "U," might be assigned to chords with only slight differences. At the same time, however, characters that are often confused should be assigned chords which are very distinct, in order to avoid mistakenly inputting one for the other.

Measures of Chord Ease

One might now ask how does one measure whether a chord is easy? A number of measures might be used. First, an investigator might simply ask people for their opinions. They could be told or shown what movements a chord involves and asked to rate the difficulty on some scale. Raji, et al. (1987) used this strategy in attempting to discover relative motor difficulty of 31 chords on their binary key keyboard. They had subjects view schematic drawings of pairs of chords, and told them to execute the chords by pressing their fingers on a table, and then to select which chord was easier. However, this exercise was not conducted on the keyboard itself (an obvious fault), and it did not allow for a change in relative ease (preference) with practice and time.

The most-often used measure of ease involves the measurement of response time. In studies such as those conducted by Seibel (1962a, 1963) and Ratz and Ritchie (1961), a horizontal row of lights indicated the combinations of keys (chords) to be activated, and time was recorded from stimulus presentation to completion of chord execution. In both studies this time period was called reaction time. The more correct definition of reaction time is the time from stimulus presentation to the initiation of a response; movement time describes the time from response initiation to response completion; and response time is the sum of reaction and movement time (Seibel, 1972; and McCormick and Sanders, 1982). (See Figure 7.) The apparent misnomer in the literature might not be considered erroneous, since even Luce (1986, p.2) states that "response time is the generic term and reaction time refers only to experiments in which response time is made the major focus of attention for the subject." In this paper, however, the definitions of response, reaction and movement time described above and in Figure 7 are used.

The reason for using response time of individual chords goes back to one of the basic goals of keyboard improvement: to increase typing rate. If the easiest chords are executed the quickest, and these are assigned to the most frequent letters, then total execution time is minimized and typing rate increases. This idea is supported by Hayes' (1977) finding that response time to individual keys on a typewriter had a significant influence on overall typing rate.

Although response time is an important measure of chord ease, error rates for the different chords also give information about chord ease (Van Nes, 1976; Lockhead and

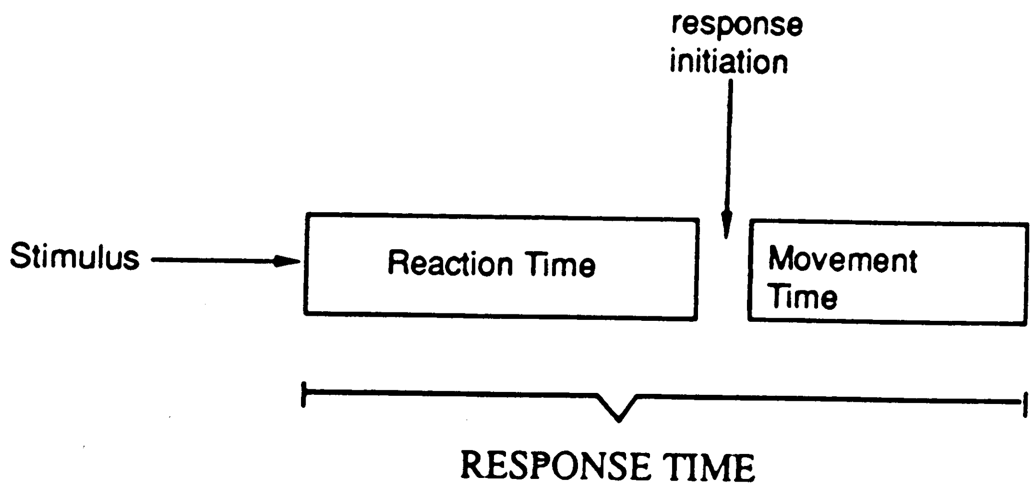


Figure 7. Response, reaction, and movement time.

Klemmer, 1959). Easier chords should involve fewer errors. Error rate becomes more important than typing speed in situations where accuracy is of prime importance, such as in a nuclear power plant or missile control system. Also, time to correct errors adds to total execution time. For the purpose of this study, however, response time is of major concern, and errors are studied only to gain information about the speed-accuracy tradeoff.

The Speed-Accuracy Tradeoff

According to Swensson (1972), errors involve shorter response times than correct responses when choices are easily discriminated and speed is stressed, but involve longer response times when choice discrimination is difficult and accuracy is stressed.

Analyzing this speed-accuracy tradeoff can take four paths. First, one variable (usually error rate) is not examined or reported. This is the worst choice, because the trends of this variable would not be known, and a change in the speed-accuracy tradeoff could occur without the investigator knowing it. Second, one variable is (assumed to be) held at a low, constant level with experimental instructions or other manipulations, and only the other variable is examined. However, the success of this technique would be unknown, since the consistency of the "constant" variable goes untested (Luce, 1986). Third, a multivariate analysis of response time and error rate could be done. The problem with this approach is that the distribution of errors often violates variance assumptions of parametric testing, by having a non-normal distribution which is often skewed towards zero. Thus, parametric statistical procedures cannot be used, or at least, inferences based on their results would be viewed with suspicion. Therefore, the two variables must be tested separately. Finally, only response times of correct responses may be studied. The problem with this is that in some experimental situations subjects might use more of a guessing strategy than in other situations. When average response times are computed, correct responses that were guessed might change this average for some situations and not for others, and findings of significant factor effects might be erroneous (Luce, 1986). Without error data, this confounding effect would never be known.

Another problem with regard to errors has become evident in previous studies on the TCK. Subjects consistently pause after errors, even when instructed not to do so. This adds to the response time of the trial following the error. If this pausing is not done with the same frequency during all experimental situations, the average response time of some may be raised unnaturally.

The solution to this problem and to the speed-accuracy tradeoff problem is involved, but quite simple. First, response times of errors are excluded from the main statistical analyses, because they do not represent a true execution of the desired response. When a TCK chord other than the one cued is executed, it is not a true measure of the time it takes to execute the correct chord, but a measure of incorrectly identifying and executing another chord. The average of response times of errors, however, is compared to the average correct response time to see if there is a significant difference between the two. Second, the number of errors in all experimental situations is recorded and studied to discover if a different strategy was used by subjects under different experimental conditions.

In addition, the average response time of correct trials that do and do not follow errors is compared to discover if there is a significant difference between the two. If the difference is significant, only those trials that do not contain or follow errors are analyzed.

If a significant difference is not found, it is assumed (but not proven) that there is no difference between response times of trials that follow errors and those that do not. All correct trials are then analyzed.

Separation of Reaction and Movement Time

The idea that differences in chord response times are due to differences in the movement time is based on two studies. First, Rumelhart and Norman (1982) stated that perceptual and cognitive factors are important only in the very early stages of typing, but the motor factor is the most important from then on. Also, Ratz and Ritchie (1961), using a cueing strategy very similar to the one used in this present study, stated that "Since lights, fingers, and keys are in direct correspondence, the stimulus-response codes are highly compatible; that is, mental-recoding of the information is avoided" (p.303).

It must be noted, however, that Gopher (1986; and Gopher, Karis, and Koenig, 1985) concluded from experiments on his ten key, two-handed keyboard that the difficulty of the chords was determined by visual representation within the mental processing stages of response time, as well as by motor difficulty. He also stated that these higher level functions did not become bypassed as people became more practiced. In other words, he is in opposition to Rumelhart and Norman's belief that the effects of perceptual and cognitive factors diminish with practice.

However, because Gopher's experimental procedure included a character assignment to the chords, so that subjects had to go through the mental process of remembering what chord produced what character, and then execute this chord, his findings are not believed to apply to this experimental paradigm. Therefore, Rumelhart and Norman's and Ratz and Ritchie's idea that movement time determines chord difficulty was adopted for this experiment. With this in mind, a way must be found to separate movement time from reaction time within our pilot study procedure.

Frowein and Sanders (1978) used a common method for separating movement and reaction time. The subject's task in their experiment was to hit one of four buttons in response to a signal. This action was begun with a finger on a release button. Reaction time was defined as the time from stimulus presentation to release of the release button, while movement time was the time from this release to activation of a target button. A similar method was used by Hilgendorf (1966) to study typing reaction and movement time. Subjects' fingers were kept on home row keys until a stimulus for the keys to be hit was given. Reaction and movement time were measured as above, with the home row key acting as the release button. However, when operating the TCK, fingers must be kept on the eight keys at all times. This eliminates the above technique as an option.

Another method of separating reaction and movement time involves the recording of EMG s. However, this technique is believed to be too intrusive in a typing task of this sort.

In addition, the technique used in the pilot study may measure the differences in chord movement times. It is just not known if this measure was confounded by visual and mental processing times. A way is needed to discover if the differences in chord response times found in our pilot study were caused by the way the chords were cued, by mental processing, or by the movement time.

Donders' Subtraction Method

One way to divide response time into its components is Donders' Subtraction Method. Donders theorized that from stimulus presentation to some response there existed a number of discrete stages (Donders, 1969). He enumerated twelve such stages. A more popular model of response time includes five stages (Smith, 1968; Sternberg, 1969). These stages are stimulus encoding, stimulus identification, response selection, response execution, and movement time. Their relation to reaction and movement time is shown in Figure 8. While there are other models, and the assumptions of this model have been criticized (Pieters, 1983; Taylor, 1976; and Townsend, 1984), it is used in this paper. The reason for this and a resolution of some of the criticisms are explained further on in this discussion.

Donders used three time measures to determine the time taken by different stages. These measures were choice response time, simple response time, and contingent response time. He stated that choice response time included all five response time stages, while simple response time did not include the stimulus identification and response selection stages, since there was only one possible response to all stimuli. Contingent response time, on the other hand, did not include the response selection stage, since a response was only required for one stimulus of all possible stimuli (Gottsdanker and Shragg, 1985, and Donders, 1969). By subtracting simple response time from choice response time, one could get the time required for stimulus identification and response selection. (See Figure 9.) If simple response time were subtracted from contingent response time, the difference would be stimulus identification time. Finally, response selection could be found by subtracting contingent from choice response time.

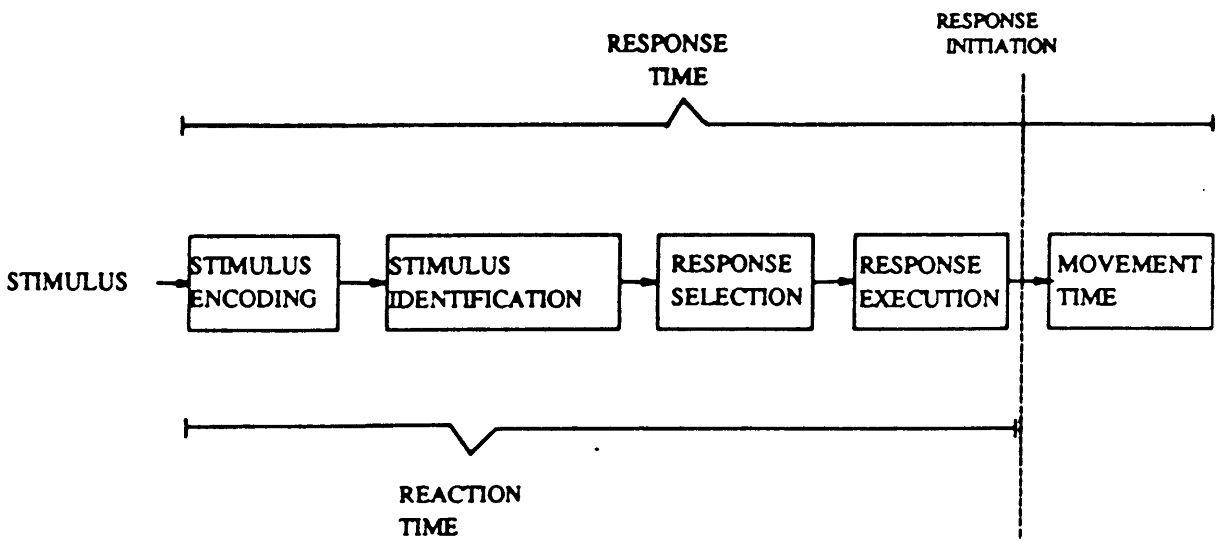
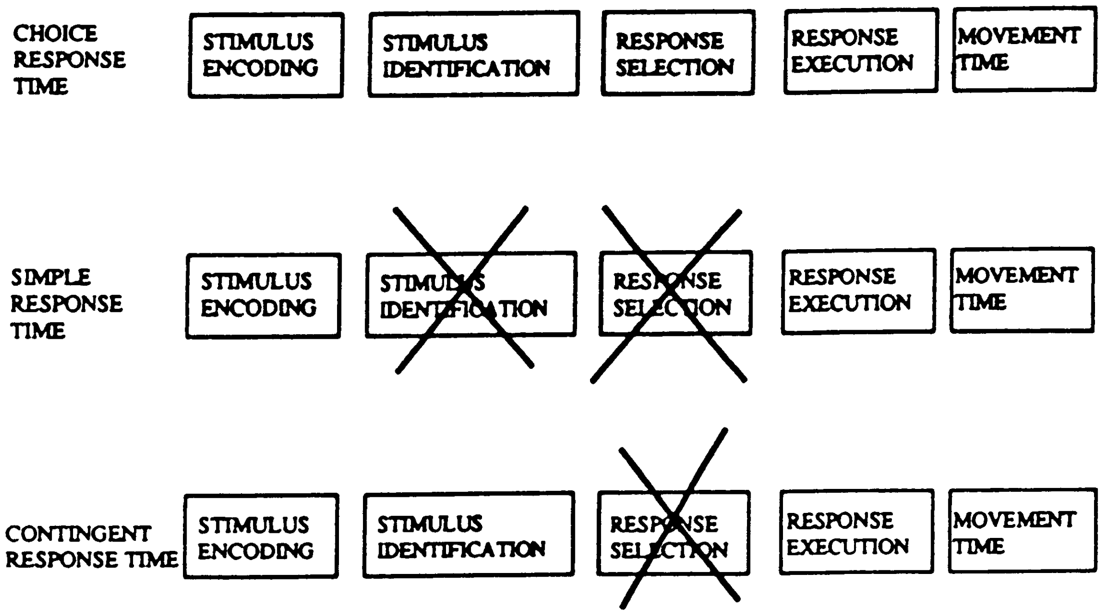


Figure 8. The five stages of response time (Smith, 1968).



CHOICE RESPONSE TIME - SIMPLE RESPONSE TIME =
STIMULUS IDENTIFICATION + RESPONSE SELECTION

CHOICE RESPONSE TIME - CONTINGENT RESPONSE TIME =
RESPONSE SELECTION

CONTINGENT RESPONSE TIME - SIMPLE RESPONSE TIME =
STIMULUS IDENTIFICATION

Figure 9. Donders' subtraction method.

This method has been criticized on two grounds. First, stages might not be strictly serial, but might sometimes occur in parallel (Miller, 1982). Second, introspective research made experimenters question whether one could delete some stages of choice response time without affecting others (Sternberg, 1969). Although Gottsdanker and Shragg (1985) verified Donders' method, at least for subtractions involving choice and simple response times, the fact remains that this technique does not provide for a separation of stimulus encoding and movement time.

Sternberg's Additive Factors Method

Sternberg proposed his Additive Factors Method, which "unlike Donders' method, does not lead to the measurement of stage durations, but like his method can be used to help establish the existence and properties of stages, and relations among them" (Sternberg, 1969, p.277). This method involves conducting a factorial experiment with two or more independent variables, with each variable having two levels, an easy level and a difficult level. The easy level involves a shorter response time than the difficult level, and this significant factor effect is used to test interactive effects on response time, the dependent variable. If two independent variables show an interactive effect, they are assumed to affect the same stage. If they are additive (show no interactive effect), they are assumed to affect different stages.

These assumptions can be explained by thinking of each stage of response time as having a limited amount of resources. If a factor that affects this stage is manipulated to cause an increase in performance difficulty, this puts an increased drain on stage resources.

Further, if an additional factor that affects this stage is introduced, more of a drain is put on stage resources. Because the two factors draw on the same resources, they have an interactive effect on performance as they compete for these resources. This is expressed as an interactive effect on the time it takes to complete this stage, and more generally, on overall response time. If factors affect different stages, they draw on separate resources, and have an additive effect on total response time.

In his original studies, Sternberg manipulated four factors: stimulus quality, number of equally likely responses, response type, and relative frequency of responses. He found non-interactive results between all of these factors. This convinced him that there were four separate stages to reaction time , and that each of the factors affects one of these stages. (These stages are shown in Figure 8.) He theorized that stimulus quality affects the stimulus encoding stage, number of equally likely responses affects the stimulus identification stage, response type affects the response selection stage, and relative frequency of responses affects the response execution stage.

Many studies have been done using the Additive Factors Method. Using the four-stage model of reaction time, much knowledge of additive and interactive effects between different factors has been compiled. Wickens (1984) gives a summary of these results.

Problems With the Additive Factors Method

Despite its usefulness, there have been criticisms of the Additive Factors Method, and warnings as to when and how it should be applied. A number of these were given by Sternberg (1969) himself. A discussion of problems which affect the present study follows.

First, experimental confounds cloud additivity more than interaction (Sternberg, 1969). Also, with the use of analysis of variance to analyze data, significant interactions show that factors affect at least one stage in common, but nonsignificant interactions do not necessarily indicate that the factors affect different stages (Taylor, 1976; Pieters, 1983; and Townsend, 1984). For these reasons, Taylor suggests using the Additive Factors Method to uncover interactive effects rather than additive effects. In conditions where an additive effect is of concern, an insignificant interactive effect suggests but does not prove an additive effect. The reason for this is that in an analysis of variance, additivity is the null hypothesis. In setting a significant alpha level, one is primarily concerned with Type I error, or wrongly rejecting the null hypothesis. But while choosing a small alpha level, one raises the probability of a Type II error, or wrongly failing to reject the null hypothesis. Because of this, in this study the effects of primary interest are interactions. As a warning, the statement must be made that one can never truly accept the null hypothesis, but can only fail to reject it. However, in this experiment, when a nonsignificant effect is found, the null hypothesis is assumed, but not proven, to be true.

Second, if stages are truly not independent, not additive, and do not occur sequentially, conclusions drawn from analyses may be erroneous (Sternberg, 1969). These characteristics of stages have been brought under scrutinity (Miller, 1982; McClelland, 1979; Ashby, 1982; and Luce, 1986). The argument as to how processes occur during reaction time has proponents on both sides. There is evidence both for and against the use of the Additive Factors Method. For the present experiment, the sequential, independent, additive notion of stages is accepted as a tool, not as an absolute truth. Because a definite answer is not now known, especially as it involves a paradigm like the one used in this experiment, caution should be used in interpreting results and conclusions.

Third, Sternberg's method does not provide for an analysis of a possible speed-accuracy tradeoff (Luce, 1986). In fact, his method is hardly concerned with errors at all. Luce states that in using the Additive Factors Method, experimenters either record error frequency for each experimental factor and check to see if there are any systematic effects, or simply discard trials with errors in them. He goes on to say that "neither procedure is really satisfactory to those that are convinced that speed-accuracy tradeoff may well reflect a deep aspect of mental processing" (Luce, 1986, p.483), and that one should study this relationship both empirically and theoretically. Luce only gives a theoretical approach which is beyond the scope of this study. Therefore, in response to Luce's warning, an approach involving both of the above procedures is used. This fact was mentioned earlier in the speed-accuracy tradeoff discussion.

While this study depends upon the stage model used by Sternberg, it is simplified for the sake of this experiment. This simplified model is seen in Figure 10. The chord cue stage represents stimulus encoding, and the chord execution stage is movement time and, to a lesser degree, response execution. The other two stages, stimulus identification and response selection, are grouped into the one stage of mental processing.

Because the Additive Factors Method requires the investigation of interactive effects, and this requires more than one level of the factors of interest, the main effects of interest have two levels. The first involves shorter response times (easy situation), and the second involves longer response times (difficult situation).

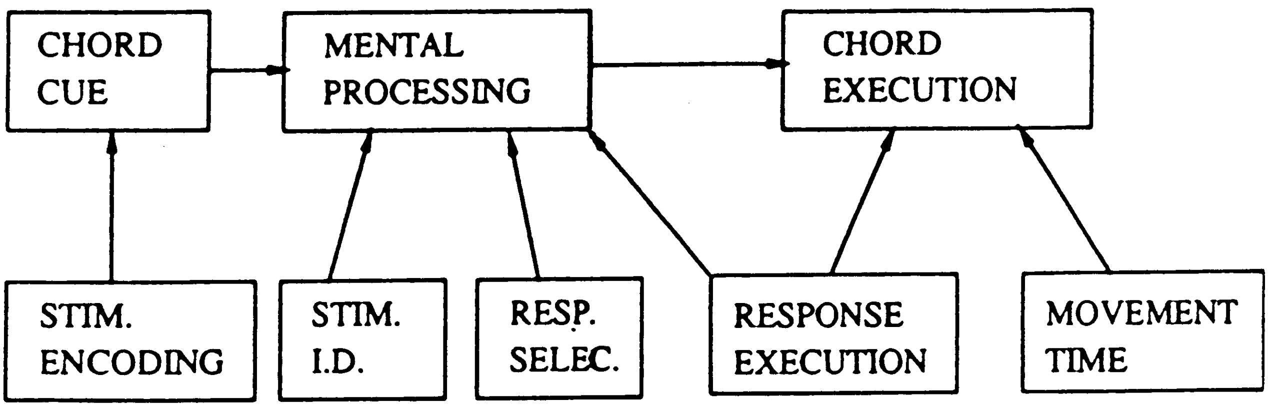


Figure 10. Simplified model of response time used in this study.

Experimental Factors

The factors manipulated in this study were practice, gender, chord ease, response repetition, and stimulus quality. While these factors are explained later in the experimental procedure section, discussions of why they are chosen, the stages they affect, and how their different levels are achieved are warranted at this time.

Practice

The practice effect takes place as subjects execute chords more and more times. The more times they do a chord, the shorter the response times. This factor is included in the experiment to investigate whether the other main effects and interactive effects change as a subject becomes more efficient at using the TCK. This increased efficiency represents the ability of a skilled chordist. Seibel (1963) found that subjects using his chord keyboard required at least 75 executions of chords before decreasing response times levelled off. In this experiment, the chords of interest were executed by each subject 100 times in all experimental situations, and this 100 times was split between four sessions, with 25 in each.

Gender

One sex often forms the majority of a population using keyboards. Secretarial typists are most often females, while military personnel who input information to a navy ship computer are predominately males. Thus, knowing if there is a difference between male and female performance on the TCK is important. To the knowledge of this author, only one study done on chord keyboards has investigated a possible difference between abilities of males and females. Cornog, Hockman, and Craig (1963) found no performance differences between the two. Therefore, while the importance of studying gender differences on the TCK is important, these differences are hypothesized to be insignificant.

Chord Ease

Chord ease is the factor of primary concern in this experiment, and is defined as the amount of time, in relation to other chords, it takes to execute a chord. A question investigated in this study is in what stage of response time this effect occurs in in the pilot study. Instead of having a chord ease factor with 64 levels, two chords were chosen to represent the two extremes of this effect. It must therefore be certain that the two chords studied are truly the easiest and hardest chords, or at least good representations, and that the difference between the two represents as many of the factors that affect chord ease as possible. Let us now turn to a discussion of these factors.

It is hypothesized that five factors affect chord ease: the fingers used, the hand these fingers are on, whether the same or different fingers are used on the two hands, whether the two keys of a chord are moved in the same or opposite directions, and the direction of key movement (fore or aft).

Finger Used

While no study has investigated which finger is the quickest in using the keys of the TCK, some conclusions might be drawn from data involving tapping and binary-key keyboards.

Since typing rate is of primary concern, tapping rates of fingers might help to determine chord ease. Dvorak, Merrick, Dealey, and Ford (1936) found that tapping rate consistently went down as one moved from the index to the little finger. They also discovered that tapping rate was higher for the fingers on the right hand, probably because of their more frequent use (Alden et al., 1972).

Table 1 gives a summary of studies that have tested individual finger response time in a typing or typing-like situation. (Since the studies describe both hands separately or only the right hand, results are given for the right hand only.) Again, these involve binary keys. As can be seen, there is little consistency as to which fingers were the quickest. This is probably due to different experimental situations, such as the cueing scheme. Despite the differences in the experiments, there should be some consistency. Its absence, and the fact that these studies involved binary keys, suggest that basing the choice of which fingers are quickest should be done on a new, highly controlled study on the TCK itself.

Table 1. Ordering of fingers on the right hand according to response time. (Note: 1 = fastest, 4 = slowest)

AUTHOR(S)	FINGER			
	Index	Middle	Ring	Little
Kiesow (1910, cited in Gatewood, 1920)	3	1	2	4
Gatewood (1920)	2	4	3	1
Ratz and Ritchie (1961)	4	2	3	1
Seibel (1962a)	3	2	1	4
Hayes and Halpin (1978)	4	3	2	1
Bartram and Lee (1985)	2	3	---	1
Raji, Gopher, and Kimchi (1987)	2	1	3	4

Hand Used

Gatewood (1920), Hayes (1978), and Dvorak et al. (1936) suggest that fingers on the right hand are quicker than those on the left. However, there is no mention of handedness of subjects, so one wonders if this factor might have a confounding effect, since most people are right-handed. Also, Bartram (1985) found no difference in response time for fingers on the two hands. Gopher (1986) found that response times were shorter for the left hand, even when subjects scanned cues (Hebrew letters) from right to left, thus eliminating the effect of "seeing" the left cue first. Gopher continued by presenting an interesting idea of why the left hand is believed to be quicker in executing chords. He brings up the the common held belief that spatial patterns are localized in the right side of the brain (Allen, 1983). He goes on to say that actions involving spatial patterns (such as chording) are done more quickly by the left hand because it has a more direct path to the right side of the brain, while the right hand must receive signals from the left side of the brain, which in turn must come the right side of the brain across the corpus callosum. While this is a compelling argument, the answer as to what hand performs actions quicker on the TCK should be found by experimenting on the TCK itself. In no previous studies involving the TCK were subjects asked about hand differences.

Finger Symmetry

Intuitively, it seems that chords involving the same finger on the two hands would be easier than those that involve different fingers. Lockhead and Klemmer (1959) considered chords that were bilaterally symmetrical to be easier, although this was not based on research. Unfortunately, only one of the other chord keyboard studies even attempts to report an answer to this question. Gopher, Karis, and Koenig (1985) investigated the benefits of two types of finger symmetry. Their ten key chord keyboard had a cueing scheme similar to the one used with the TCK. They wanted to see if visual or proprioceptive symmetry resulted in lower response times. A chord which called for pressing the left little finger key and the right thumb key would demonstrate visual symmetry, since both presses involve the left most key in one of the two groups of five. Pressing the two index finger keys would demonstrate proprioceptive symmetry, since the same fingers were used. They found that chords that involved visual symmetry were quickest, and that when the two types of symmetry were combined, chords were executed even more quickly. This study suggests the benefit of finger symmetry (and also the importance of visual factors when performing chords).

An answer to this question might also be drawn from general finger response time experiments. Gatewood (1920, p.35) reports that "there seems to be no reason for concluding that symmetrical movements are faster than those two-finger movements that are not symmetrical." On the other hand, Rabbitt, Vyas, and Feamley (1975) found faster response times when symmetrical fingers were used than when assymetrical fingers were used. Previous subjective questioning of users of the TCK, however, indicated that nine of twelve of them thought that chords involving finger symmetry were easier than those chords that did not. Again, the conclusion seems to be that an answer cannot be drawn from previous studies, and must be found from studies on the TCK itself.

An interesting note on finger symmetry is Gopher's (1986) finding that of the two movements of the hands in a chord, the easier movement seems to slow down to wait for the harder. It might therefore be suggested that only the harder movement be studied to scale chord response times.

Movement Symmetry

Another factor affecting chord ease is whether the key movements performed by the two hands are in the same or opposite direction. This factor has not been studied before, because no keyboard has used a ternary key. However, an answer to the question of movement symmetry can be drawn from a series of studies by Heur (1982a, 1982b, 1982c, 1985). He found that the selection of the finger used in a movement is done for each hand separately, while the selection of the form of the finger movement is done jointly for the two hands. Thus, using different fingers on the two hands might not increase response time as much as performing a different movement on them, since this second action involves an inhibiting action on the pre-decided movement and then the execution of another. In other words, two selections are made instead of one, and this takes more time. These notions do suggest that a chord involving symmetrical movement is easier. In addition, subjective questioning of TCK users indicated that symmetrical chords "felt" easier. Once again, it is seen that new questions raised by the TCK require new experiments to answer them.

Aft or Fore Key Displacement

Finally, one might ask what key direction is easier to execute. As was the case of movement symmetry, this question has not been addressed in previous studies on chord keyboards, since they used binary keys. The only evidence in the literature that seems related to this question involves the muscles used in moving the keys forward (i.e., finger extension) and backward (i.e., finger flexion). Brand (1985, p.273) states that "the tension capability of all of the forearm muscles that extend the fingers is about 38% of the tension of all the forearm muscles for finger flexion." Whether this answers our question is doubtful for three reasons. First, the force required to move the TCK keys (0.7-1.0 N) is small. Second, it has been observed that slight movements of the whole arm are often made when operating the TCK keys. This might make mute the consideration of the differences in finger extension and flexion capabilities. Finally, subjects have indicated that they sense no difference in difficulty between moving the TCK keys forward or backward.

At the risk of being redundant, it must be stressed that the present literature offers little help in answering our question about chord ease on the TCK. New studies must be done for conclusive answers. Thus, the choice of chords representing the two chord ease levels, while incorporating some of the data from the literature, is primarily based upon the findings of the pilot study and other studies on the TCK.

As a final note, it might also be that one cannot predict the ease of chords by analyzing the characteristics of chords. It might be as Raji et al. (1987) state: "To understand and describe chord complexity, it is necessary to analyze the specific nature of each chord" (p. 821).

Response Repetition

The fourth factor in this study that needs to be explained is response repetition, which is believed to affect the chord execution stage, and to some degree, response execution. The easy level involves executing the cued chord once, while the difficult level involves executing it twice. Response times were recorded for both executions in the difficult level.

Because the subject is told ahead of time to execute a chord twice in response to one cue, it is believed that not all of the stages of reaction time (with the possible exception of response execution) are required in the second execution. The subject simply reiterates the chord that has already been encoded, recognized, and whose motor program has already been selected.

This idea is based on three thoughts. First, in the release and target button paradigm for separating reaction and movement time mentioned earlier (Frowein and Sanders, 1978; and, Hilgendorf, 1966), the release of the release button marks the end of reaction time. In the same manner, the first execution of the cued chord in this experiment indicates visual and mental processing have been finished. Second, some investigators who attempt to study movement time give subjects a preview of the stimulus, allowing them to conduct their visual and mental processing. A trigger signal is then given for them to execute the response that has theoretically already been prepared (Sheridan, 1981). Thus, the only time involved is the movement time and the constant time of recognizing the trigger stimulus. The technique used in this study also assumes that the visual and mental processesing is finished before the first execution, and that it does not have to be repeated for the second. Finally, Wickens (1984) states that in transcription tasks such as typing, responses can be made more quickly and closer together because visual and mental processing is done for groups of responses, not just one, and this processesing is not required between responses. This is believed to hold true in the present experiment, since not only are two chords typed in succession, but they are the same chord, and subjects know they will be the same chord ahead of time.

It makes some sense, however, that response execution might, to some degree, occur twice. Response execution includes retrieving the chord motor program, converting it into a motor nerve signal, and conducting that signal to the muscles that move the fingers (Smith, 1968). Most likely, however, the only part of this process that needs repeating is the signal conduction, since any separate movement must include a nerve impulse to initiate it. Even if these arguments are untrue, the question of whether response execution is involved in the second execution might be unimportant, since the time for this process to occur is probably very small in relation to chord execution time, both in this study and in an actual typing task.

It is intuitively obvious that this second execution increases chord response time. As seen in Figure 11, if the second execution increases response time differently for the difficult and easy chord (thus showing a chord ease-response repetition interaction), then the chord execution times of the two chords are different (the chord ease factor affects the chord execution stage). This follows, since the increase in response time represents the chord execution time of the chord. (Figure 12 shows the case of an additive effect between chord ease and response repetition.) This explanation is used in addition to Sternberg's Additive Factors Method because it removes the need for dependence on a response time model, something which is preferred in light of the problems of such modelling. A similar explanation is used for the stimulus quality-chord ease interaction in the *Discussion* section of this paper.

Stimulus Quality

According to Wicken's (1984) summary mentioned earlier, and Sternberg's (1969) original study, stimulus quality affects the stimulus encoding stage. Logically, stimulus

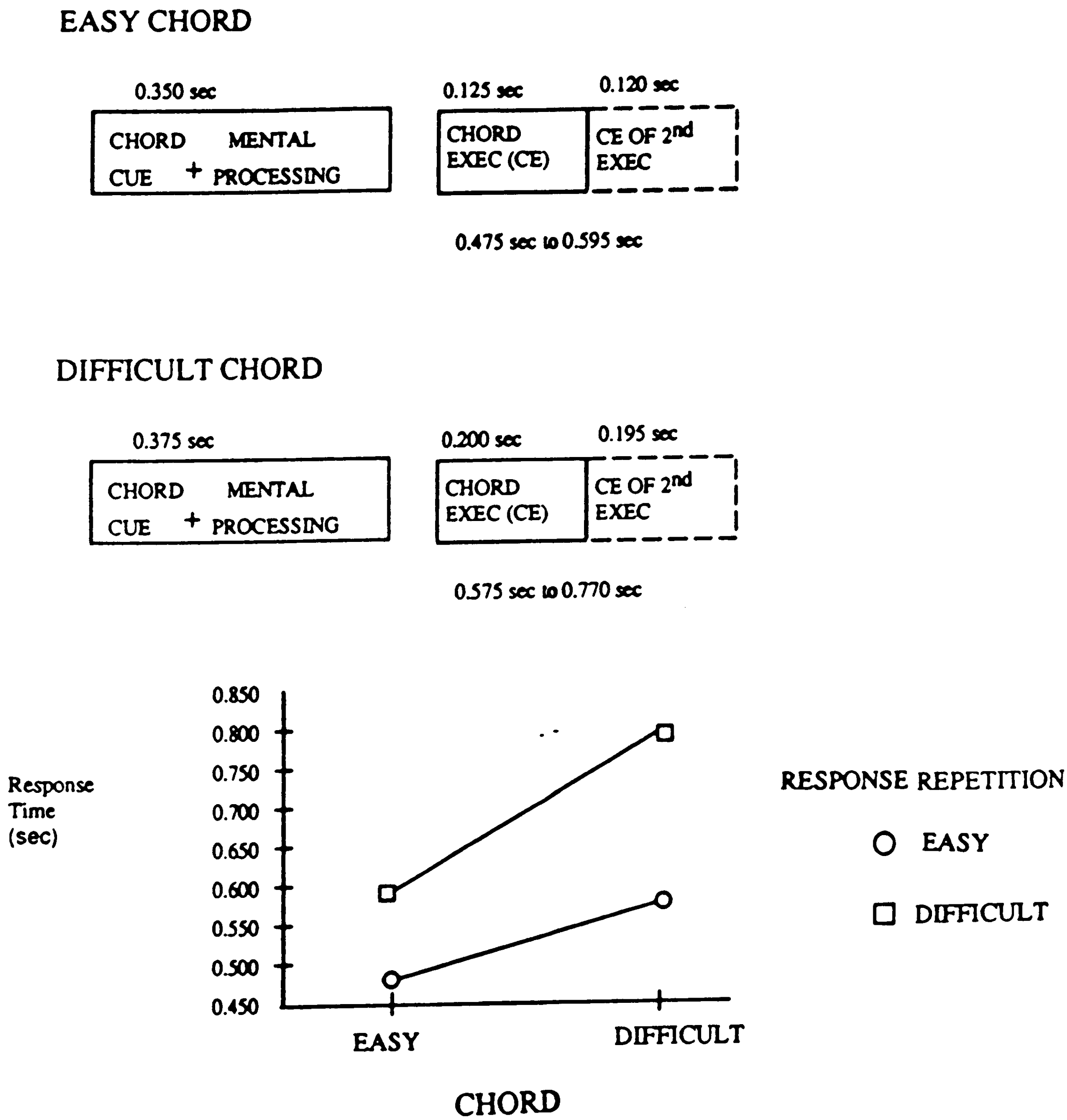


Figure 11. Interactive effect between chord ease and response repetition (hypothetical data).

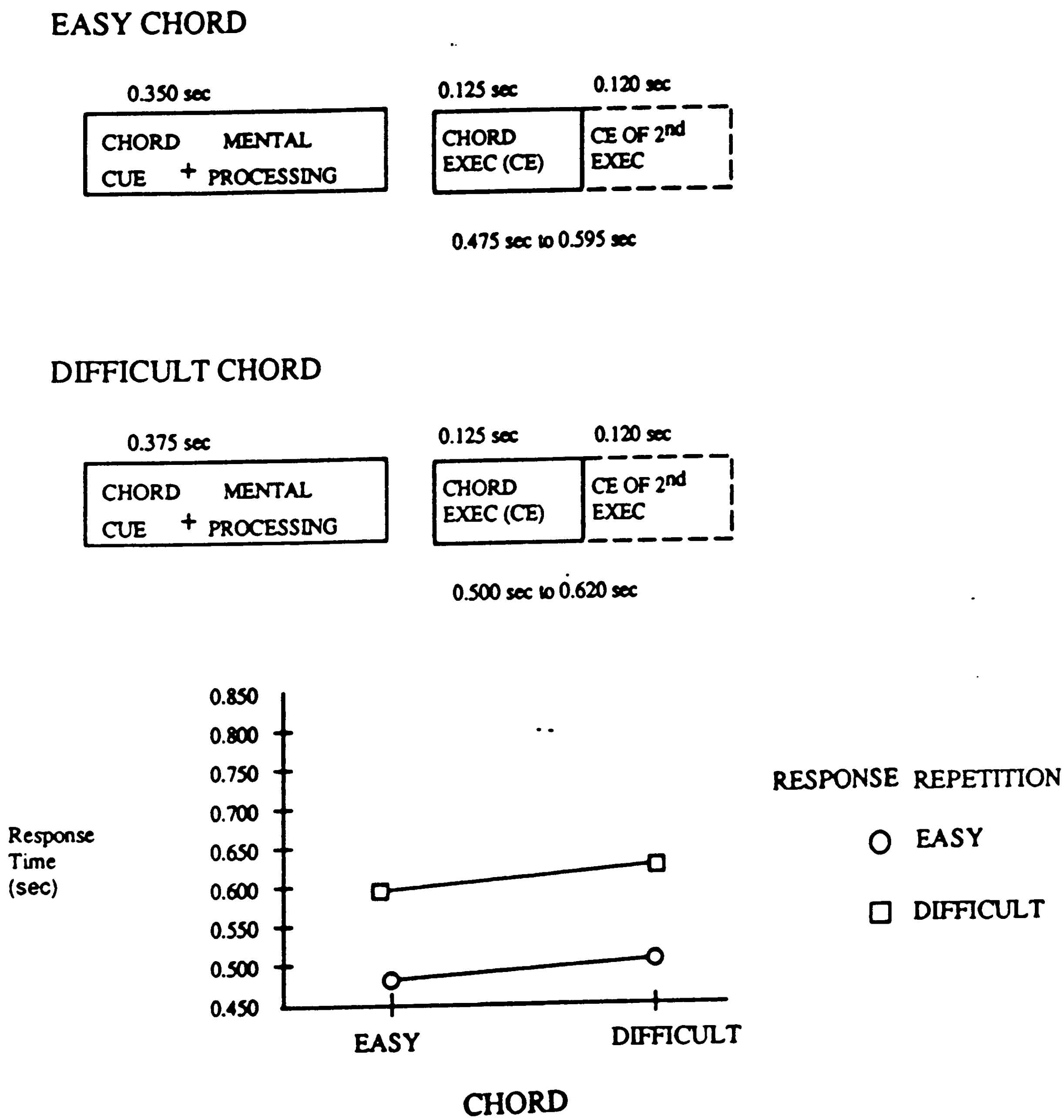


Figure 12. Additive effect between chord ease and response repetition (hypothetical data).

quality should also affect the time it takes for subjects to encode what chord the cueing scheme represents.

The original cueing scheme used in the pilot study is seen in Figure 6 and in Figure 13. This scheme represents the easy level of stimulus quality. The difficult level of stimulus quality is achieved by removing the shading from the displaced "key," and cutting the displacement in half. (This is shown in Figure 13.) In this way, the encoding of which keys are displaced, and therefore of the chord these displaced keys represent, takes longer in the difficult level.

This is supported by Fisher, Coury, Tengs, and Duffy (1989), who state that highlighting on CRTs reduces visual search (stimulus encoding) time by drawing a person's attention to the highlighted item. Thus, the easy stimulus quality situation, which includes such highlighting in the form of shading the displaced boxes, involves less time than difficult situation, which does not; and this difference will take place in the stimulus encoding stage. In addition, a preliminary investigation revealed that chords cued using the difficult stimulus quality situation did take longer to execute than those that were cued using the easy stimulus quality situation.

This difference in response time between the two stimulus quality levels is studied, using the Additive Factors Method, to see if there is an interaction between chord ease and stimulus quality. If there is a significant interactive effect, then by Sternberg's rules the chord ease effect occurs in the chord cue (stimulus encoding) stage, and differences in chord response times in the pilot study were confounded by the way the chords were cued. As mentioned earlier, an explanation of the results that does not involve Sternberg's method is also given.

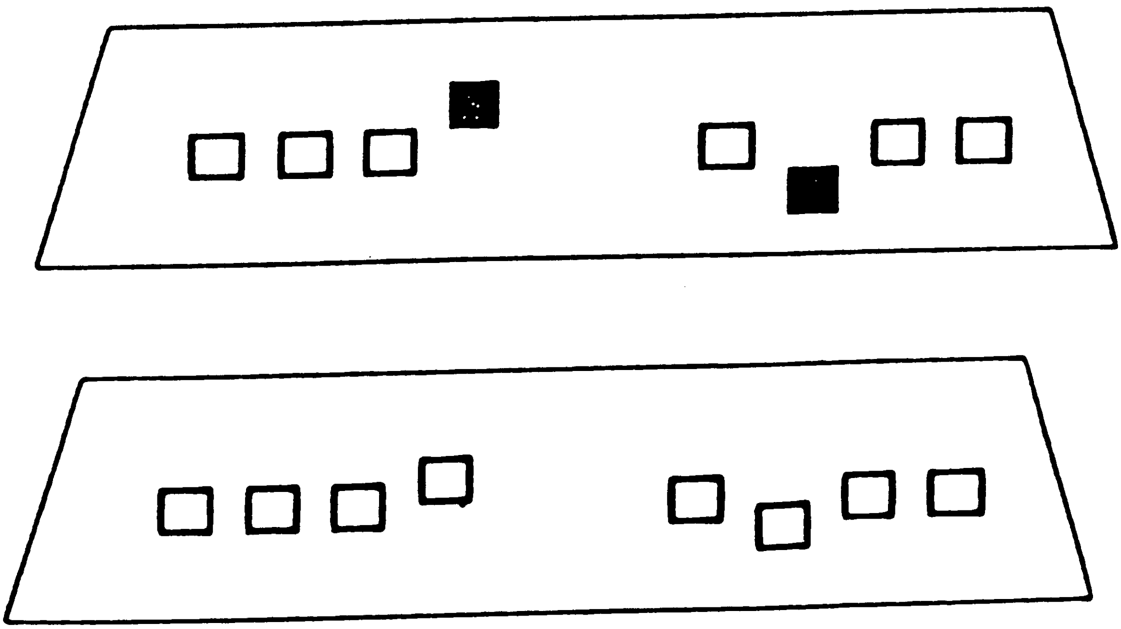


Figure 13. Easy (top) and difficult (bottom) stimulus quality cueing schemes.

Hypotheses

Sternberg's Additive Factors Method was used to discover if the chord cueing scheme used in the pilot study, the actual chord execution time, or both caused differences in response times. In light of the preceding literature review, the following hypotheses are made:

1. The average response time of trials which contain errors and the average response time of correct trials will differ significantly.

2. The average response time of correct trials that follow errors will differ significantly from the average response time of correct trials that do not follow an error.

3. There will be no significant difference between male and female performance on the TCK.

4. There will be no significant interaction between stimulus quality and response repetition, suggesting that the two affect separate stages.

5. There will be a significant interactive effect between chord ease and stimulus quality, but not a significant three-way interactive effect among chord ease, stimulus quality and practice, together indicating that the chord cueing scheme used influences chord reponse times differently, regardless of practice level.

6. There will be a significant interactive effect between chord ease and response repetition, but an insignificant interaction among chord ease, response repetition, and

practice, together indicating that the difference in chord response times occuring in the chord execution stage is exposed by the pilot study paradigm, and that this difference does not change significantly with practice.

Method

Subjects

Twelve subjects participated in this study, six males and six females. All were college students and were paid for the time spent in the experiment. Their ages ranged from 19 to 24 years, with an average of 21.75.

When subjects were contacted to participate in the experiment, they were asked the following questions:

1. Can you type without ever looking at the keys?

2. Have you had more than casual experience with a musical instrument that involves chording, such as the piano, organ, or saxophone?

3. Have you had any experience with or been in a study involving the use of a chord keyboard?

If the subject answered "no" to all three of these questions, he/she was assumed to have no prior experience that could give an advantage over others in regard to performance and learning on the TCK, and was therefore allowed to participate in the experiment. The first question was asked despite the findings of Fathallah (1988) and Gopher (1986) that experienced QWERTY typists had no advantage over novices when typing on a chord keyboard, because Klemmer (1958) found that experienced QWERTY typists made more errors than novices on a chord keyboard.

Experimental Apparatus

The experimental apparatus included the TCK, which was interfaced with a IBM PC AT. A program was written to recognize TCK inputs and to collect all pertinent data.

Experimental Design

This study involved a 2x2x2x2x4 factorial mixed design. The five factors of interest were chord ease, stimulus quality, response repetition, practice, and gender.

The first independent variable was chord ease, a fixed-effects, within-subject variable consisting of two levels: easy and difficult. The easy level involved executing what was thought to be the fastest (easiest) chord: both index finger keys fore. Since it was desired to take as many of the factors that affect chord ease (as described in the literature review) as possible into consideration, the difficult level of chord ease involved moving the left ring finger key aft and the right middle finger key fore. This chord involved using two of the slower fingers, and did not use the advantage of finger or movement symmetry. It was also one of the chords with the longest response times in the pilot study. Finally, it involved a representation that did not have the advantage of anchor points to help identify the keys to be activated.

The second independent variable was stimulus quality, a fixed-effects, within-subject variable with two levels: easy and difficult. These levels were accomplished by leaving the screen as it was in the pilot study for the easy condition, and by removing the shading of the displaced key and cutting the displacement in half for the difficult level.

The third independent variable was response repetition, a fixed-effects, within-subject variable with two levels: easy and difficult. The easy level was accomplished by executing the cued chord once and the difficult level by executing it twice in response to only one cue.

The fourth independent variable was practice, a fixed-effect, within subject variable with four levels: sessions 1, 2, 3, and 4.

The fifth independent variable was gender, a fixed-effect, between subject variable with two levels: male and female.

Dependent Variables

There were two dependent variables collected throughout the experiment: response time and number of errors. Number of errors was totalled for every experimental situation.

Response time was collected for every trial and was identified in eight ways: by subject, gender, practice level, response repetition level, stimulus quality level, chord ease level, trial number, whether the trial was correct, and whether the trial followed an error. A response was defined as incorrect (an error) if one of the 63 possible chords that were not cued were executed, and a correct response was defined as one in which the cued chord was executed. As is explained later, subjects had no chance to correct errors, so there was only one response per trial (cue).

It must be noted that these 63 other chords were not the only mistakes that could have been made. Subjects could have activated keys on only one hand, and the computer would not indicate this as an error. It simply waited for a key on the other hand to be activated. Also, if more than one key on a hand was activated, the computer would recognize only the first one activated. However, because of observation in previous studies and conversation with subjects, errors of this nature are believed to be very rare, and should not affect the results of this study.

Experimental Procedure

On the first day of his/her involvement in the experiment, each subject read and signed a consent form. (See Appendix A.) The subject was then told the general nature of the study, allowed to read written directions for procedure (See Appendix B.), and introduced to the TCK. The instructions were then read to the subject, and the experiment began.

The experimental procedure had three basic components: sessions, blocks and trials. There were four sessions, each of which represented one level of the practice effect. Within each session there were two blocks. Each block represented one of the two levels of the response repetition effect. Three of the male and three of the female subjects first executed the chords once, and the other three of each gender first executed the chords twice. The actual choice of what subjects got what level first was random.

If only the two chords representing the two levels of chord ease were cued and executed, several problems would have emerged. First, subjects might have fixed their stimulus scanning exclusively on the four "keys" involved in these chords. Also, they might have learned that if a certain left-hand key movement was cued, then a particular right-hand key movement would always be paired with it. With this knowledge, they might not have bothered to check the right-hand cue. Either way, the scanning technique would not have been the same as that used in the pilot study when all 64 chords were cued. For this reason, additional "dummy" chords were included.

Another reason for including the dummy chords was that the task of identifying, choosing, and going from one chord to another had to be as similar to the pilot study as possible. Therefore, fourteen additional chords were cued and executed, but measures were not recorded. This also allowed for a sufficient number of trials per chord to be done and recorded in each block. The additional chords are shown in Table 2.

Table 2. The 14 additional "dummy" chords.

Left little fore/Right index aft	Left middle aft/Right little aft
Left little fore/Right ring aft	Left middle fore/Right index aft
Left little fore/Right middle aft	Left middle fore/Right index aft
Left little fore/Right little fore	Left middle fore/Right middle aft
Left ring aft/Right index aft	Left index aft/Right middle fore
Left ring fore/Right ring aft	Left index aft/Right little aft
Left ring fore/Right little fore	Left index fore/Right ring fore

The 16 chords as a group have a number of characteristics which make them representative of the entire set of 64. First, all fingers are used in the same number of chords (4). Second, all key movements are used in the same number of chords (2). Third, the number of chords that involve moving two keys in the same direction is the same as the number of chords that involve moving two keys in opposite directions. Finally, each finger on the left hand is paired once in a chord with every finger on the right hand.

Within each block, each of the two chords representing the two levels of chord ease was presented twenty-five times in the easy stimulus quality situation and twenty-five times in the difficult stimulus quality situation, for a total of 100 presentations and executions, or 100 trials. The additional fourteen chords were cued fifteen times each in each of the two stimilus quality situations, for a sum of 420 "dummy" trials. There was therefore a total of 520 trials per block. It is believed that subjects did not notice the difference in occurrence between the measured and dummy chords. The order in which the sixteen chords were presented and the stimulus quality situation in which they were presented was random within each block.

A chord was represented on a CRT in the form of eight squares, each square corresponding to a key on the TCK. This representation (shown in Figures 6 and 13) indicated the two keys to be moved (one by each hand) and the one of two directions in which they should be moved.

The subject was required to move the keys in the way that the screen indicated. The computer recorded the time between stimulus presentation and the completion of an "acceptable" chord. An acceptable chord was one which involved the displacement of one key on each hand, for a total of 64 possible acceptable chords. The subject moved on regardless of whether a correct chord was executed, although a beep sounded to indicate an incorrect chord. The reason for this beep involves learning. It was desired that subjects know when they made a mistake, so that they would not associate the movement they made with the stimulus and make the same mistake in the future. It was hoped that this also decreased the number of errors, so that confounding effects of this variable were avoided.

Before the double response execution block in each session, the subject was told, by the experimenter and the computer screen, that the cued chord had to be executed two times in succession. If the first, second, or both inputs were incorrect, the error beep sounded after the subject had entered the two inputs.

Also, throughout the experiment, both speed and accuracy were encouraged. However, accuracy was stressed to keep errors to a minimum, in the hope of avoiding the confounding effect of a speed-accuracy tradeoff.

Data Analysis and Results

Errors

The number of errors in all 384 experimental situations was collected throughout the experiment. If one level of an effect did have more errors than another, the response times within this level might be thrown off by subjects using a different strategy for encoding, identifying, selecting, and executing the chord. Findings involving this factor might then be questioned.

Overall, only 217 errors were recorded in 9600 trials (2.26%). The numbers of errors in the experimental levels are shown in Table 3.

Table 3. Number of errors in experimental levels (* indicates significant effects.)

EFFECT	LEVEL			
Gender	Female		Male	
	163		64	
Practice	Session 1	Session 2	Session 3	Session 4
	51	49	52	65
Response Repetition	Easy		Difficult	
	107		110	
Stimulus Quality	Easy		Difficult	
	107		110	
*Chord Ease	Easy		Difficult	
	16		201	

Gender

A Mann-Whitney U test for two independent samples was used to investigate if males and females committed different numbers of errors. The difference was insignificant at the 0.01 level ($U(6,6) = 9$, $p = 0.09$), suggesting that there was no difference in the number of errors committed by males and females.

Practice

A Friedman two-way (subjects was the second variable) analysis of variance for *k* related samples was employed to discover if there was a significant change in the number of errors across practice levels (sessions). There was an insignificant result ($x(n = 6) = 0.45$, $p > 0.90$), suggesting no difference in the number of errors across sessions.

Response Repetition

To test the significance of the difference in the number of errors committed when executing a chord once and twice a Wilcoxon matched-pairs signed-ranks test was used. There was an insignificant finding ($T(12) = 30.5$, $p > 0.05$), suggesting the number of errors did not change across levels.

Stimulus Quality

A Wilcoxon matched-pairs signed ranks test for two related samples was used to investigate the possibility that the easy stimulus quality level and the difficult stimulus quality level involved different numbers of errors. The result was insignificant ($T(12)=20.5$, $p>0.05$), suggesting again that the number of errors was consistent across experimental levels.

Chord Ease

A Wilcoxon matced-pairs signed-ranks test for two related samples was also used to test if the number of errors changed across levels of chord ease. There was a significant finding ($T(12)=0$, $p<0.01$), indicating that the difficult chord involved more errors (201) than the easy chord (16).

Response Times

There were three different investigations of response time. The first compared the response time of error trials versus correct trials. The second looked at the difference in response times between correct trials that did and did not follow errors. Finally, an analysis of variance of response times was done to investigate how the five main effects influenced response time and to investigate the experimental questions.

Correct Versus Error Trial Response Times

A t test was done on the response times of correct and error trials to check for a difference in variance. There was a significant difference ($F(216,9382)=2.61$, $p<0.0001$). Because of this, and the fact that there was a big difference in sample sizes, the nonparametric Wilcoxon matched-pairs signed-ranks test for two related samples was used to determine the significance of the difference in the response time of correct and error trials. The result of this analysis was significant ($T(12)=0$, $p<0.01$), indicating a significant difference in response time for correct (1.065 sec) and error (1.477 sec) trials, with errors having a larger average response time.

Response Times of Correct Trials That Do and Do Not Follow Errors

To discover if the correct trials following errors should be excluded from the analysis of response times, the difference in the response times of correct trials that do and do not follow errors was analyzed. As a note, it should be stated that the number of trials that followed errors was not the same as the number of errors, because the two measured chords could have followed an error trial involving a "dummy" chord.

As was the case with the error versus correct trial response times, the variances of the response times of correct trials that do and do not follow errors were significantly different ($F(350,9031)=1.74$, $p<0.0001$). Therefore, the nonparametric Wilcoxon matched-pairs signed-ranks test was also used to analyze the difference in response times. This test resulted in a significant finding ($T(12)=0$, $p<0.01$), with the trials following errors (1.347 sec) having longer response times than those that did not (1.054

sec). Thus, subjects did pause after errors even though they were instructed not to. This may be a result of thinking back to discover the type of mistake, or simply a result of the beep causing a break in the subjects' concentration. Either way, correct trials that followed errors are biased in their response times by the fact that they did follow errors, and were therefore excluded from the larger analysis of response times.

Explanation of Analysis of Variance of Response Times

To discover if hypotheses 3, 4, 5, and 6 (See pages 45-46.) are correct, an analysis of variance was done involving the five main effects and their interactions.

Within each experimental situation, there were 25 repetitions. These repetitions were included to get a better approximation of the response times of chords in that particular situation. There was no interest in the variance within these 25 repetitions. Because of this, and because there were some experimental situations which involved less than 25 values due to the removal of error trials and trials that followed errors, the analysis of variance was done on the average response times involved in the experimental situations.

The Five Main Effects

The five main effects were analyzed to test their effects on response time. The average response times for the different levels of the effects are shown in Table 4.

Table 4. Average response times (in seconds) of experimental levels. (* indicates significant effects)

EFFECT	LEVEL			
Gender	Female		Male	
	1.163		0.955	
*Practice	Session 1	Session 2	Session 3	Session 4
	1.209	1.035	1.009	0.982
*Chord Ease	Easy		Difficult	
	0.8473		1.270	
*Response Repetition	Easy		Difficult	
	0.905		1.213	
*Stimulus Quality	Easy		Difficult	
	1.040		1.078	

In addition, an ANOVA table of the relevant effects is seen in Table 5, and the entire statistical model is given in Appendix C.

Table 5. ANOVA table of effects of primary interest.

Effect	df	SS	F	p	Error Term of F
Gender (G)	1	4.147	4.02	0.0728	Subject(G) or S(G)
Practice (P)	3	3.029	40.97	0.0001	P*S(G)
Chord Ease (C)	1	17.187	70.40	0.0001	C*S(G)
Response Repetition (R)	1	9.134	151.08	0.0001	R*S(G)
Stimulus Quality (Q)	1	0.141	10.73	0.0083	Q*S(G)
R*Q	1	0.020	3.73	0.0821	R*Q*S(G)
Q*C	1	0.002	0.17	0.6923	Q*C*S(G)
R*C	1	0.011	0.30	0.5932	R*C*S(G)
P*C	3	0.636	14.03	0.0001	P*C*S(G)
P*R*C	3	0.020	0.82	0.4941	P*R*C*S(G)
P*Q*C	3	0.010	0.24	0.8688	P*Q*C*S(G)

Gender

The analysis of variance showed an insignificant gender main effect ($F(1,10)=4.02$, $p=.0728$). It should also be noted that gender produced no significant interactive effects with any of the other four variables. It was therefore not included in any further analysis.

Practice

Practice had a significant effect on response time ($F(3,30)=40.97$, $p<0.0001$). However, as can be seen in Table 4, the majority of the decrease in response time occurs between sessions one and two. When a Newman-Keuls post hoc test was done to check the significance of the three decreases between sessions, only the one between sessions one and two was significant. The difference between sessions two and three and three and four were insignificant. This suggests that the speed of chord execution improves quickly when a subject first begins to type on the TCK, but that this improvement then levels off. This is examined further in the *Discussion* section of this paper.

Chord Ease

Chord ease had a very significant effect on response time ($F(1,10)=70.40$, $p<0.0001$), with the difficult chord having a much longer average response time. (See Table 4.) It seems that the choices for the easy and difficult chord were good representations of the two extremes of chords when they are placed on a difficulty (response time) scale.

Response Repetition

The response time for executing a chord twice was significantly longer than that for executing a chord once ($F(1,10) = 151.08$, $p < 0.0001$).

Stimulus Quality

There was also a significant effect of stimulus quality on response time ($F(1,10) = 10.73$, $p = .0083$), with the response time of the difficult stimulus quality level being longer than the response time of the easy stimulus quality level.

Because the stimulus quality effect had a p value close to 0.01, an analysis of the practice-stimulus quality interaction was done to see if this effect might change or decrease with practice, and possibly become insignificant within one or more sessions. The results lead to the inference that it did not ($F(3,30) = 0.69$, $p = .5657$).

Two-Way Interactions

Because all main effects were found to be significant, the analysis continued on to the two-way interactions.

Response Repetition-Stimulus Quality Interaction

The response repetition-stimulus quality interaction effect was not significant ($F(1,10) = 3.73$, $p = .0821$). The average response times of the four levels of this interaction are shown in Table 6, and the graph of these times is shown in Figure 14. The lines connecting the values of factors in the charts of all four two-way interactions are for illustrative purposes. Parallel lines suggest additivity, while lines with different slopes suggest an interaction.

Table 6. Average response times in the response repetition-stimulus quality interaction.

Response Repetition Level	Stimulus Quality Level	Average Response Time (sec)
Easy	Easy	0.878
Easy	Difficult	0.931
Difficult	Easy	1.201
Difficult	Difficult	1.225

Stimulus Quality-Chord Ease Interaction

The stimulus quality-chord ease interaction was insignificant ($F(1,10)=0.17$, $p=.6923$). The average response times for the four levels of this interaction are shown in Table 7, and the graph of this interaction is shown in Figure 15.

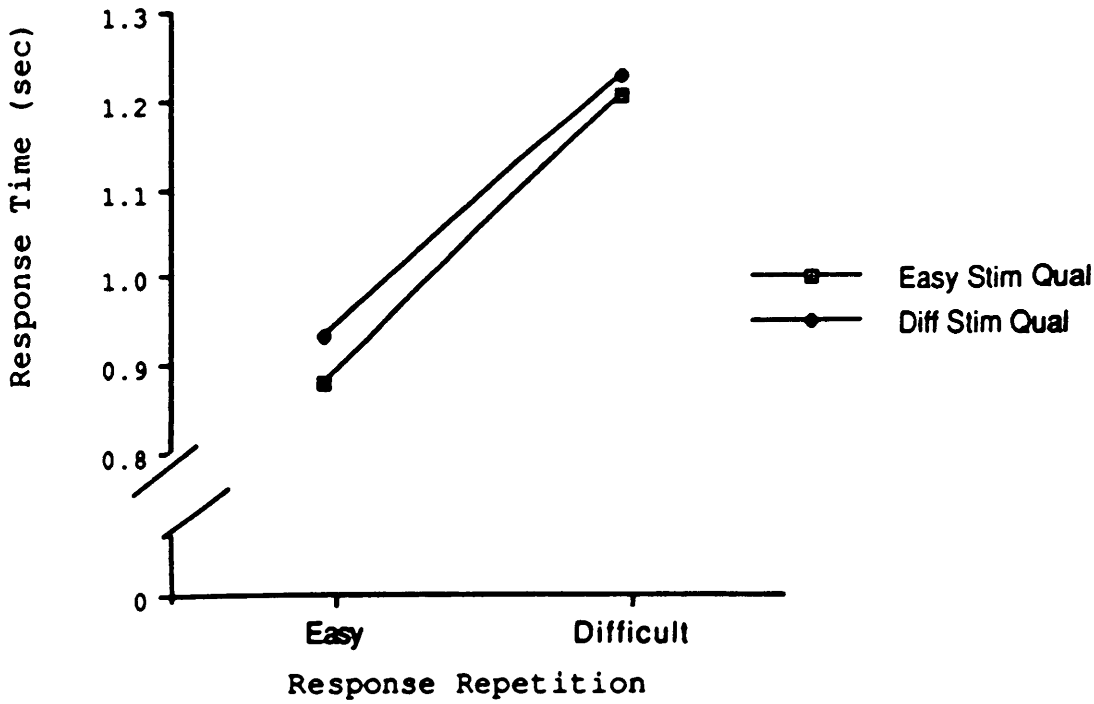


Figure 14. The response repetition-stimulus quality interaction effect.

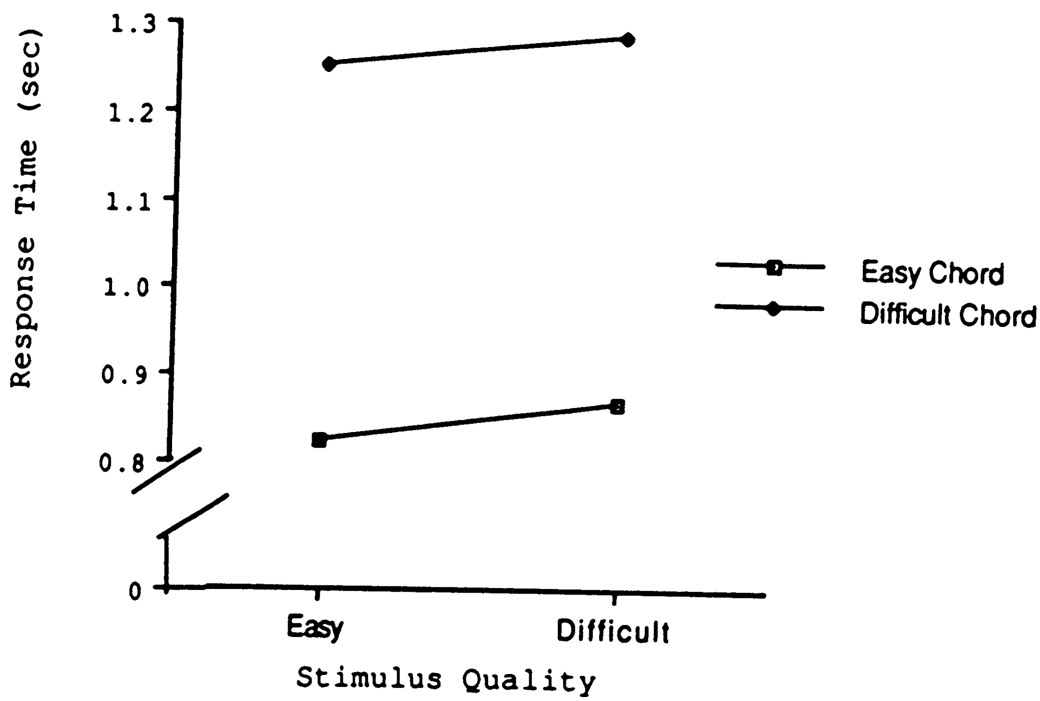


Figure 15. The stimulus quality-chord ease interaction effect.

Table 7. Average response times in the stimulus quality-chord ease interaction.

Stimulus Quality Level	Chord Ease Level	Average Response Time (sec)
Easy	Easy	0.826
Easy	Difficult	1.254
Difficult	Easy	0.869
Difficult	Difficult	1.287

Response Repetition-Chord Ease Interaction

The response repetition-chord ease interaction was also insignificant ($F(1,10)=0.30$, $p=.5932$). The average times for the four levels of the response repetition-chord ease interaction are shown in Table 8, and the graph of these times is shown in Figure 16.

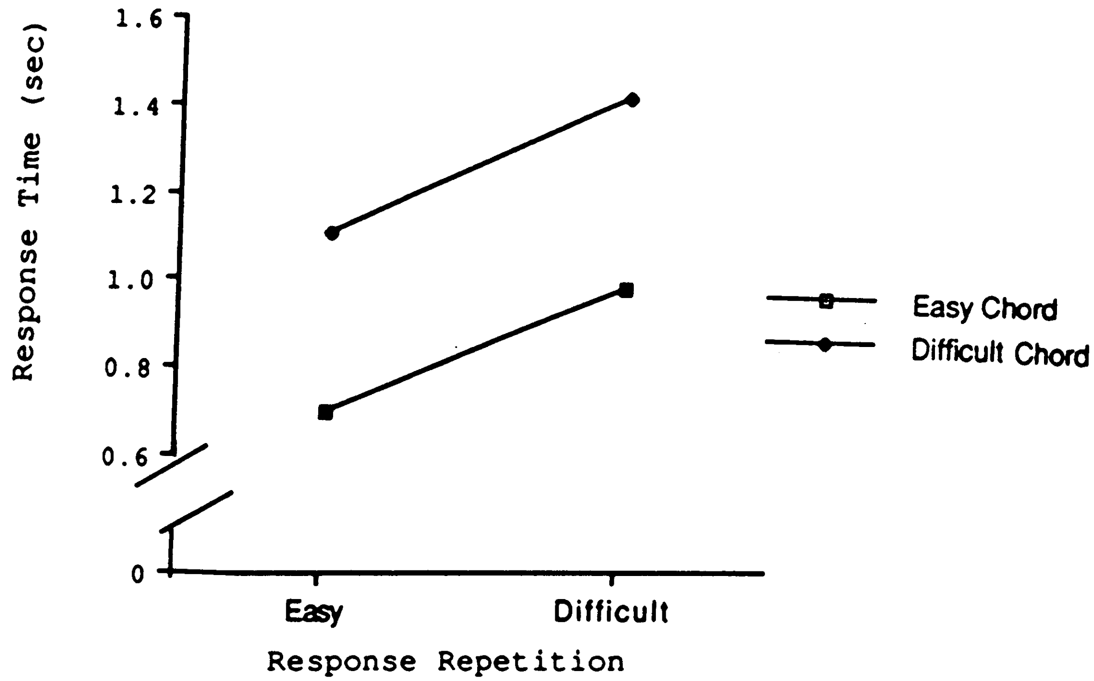


Figure 16. The response repetition-chord ease interaction effect.

Table 8. Average response times in the response repetition-chord ease interaction.

Response Repetition Level	Chord Ease Level	Average Response Time (sec)
Easy	Easy	0.698
Easy	Difficult	1.111
Difficult	Easy	0.996
Difficult	Difficult	1.430

Practice-Chord Ease Interaction

The practice-chord ease interaction was checked to determine if it would be worthwhile looking at the two three-way interactions of practice-stimulus quality-chord ease and practice-response repetition-chord ease. These three-way interactions would tell if the response repetition-chord ease and stimulus quality-chord ease interactions changed across practice sessions.

There was a significant practice-chord ease interaction effect ($F(3,30)=14.03$, $p<0.0001$). The average response times for the levels of this interaction are shown in Table 9, and the graph of these times is shown in Figure 17.

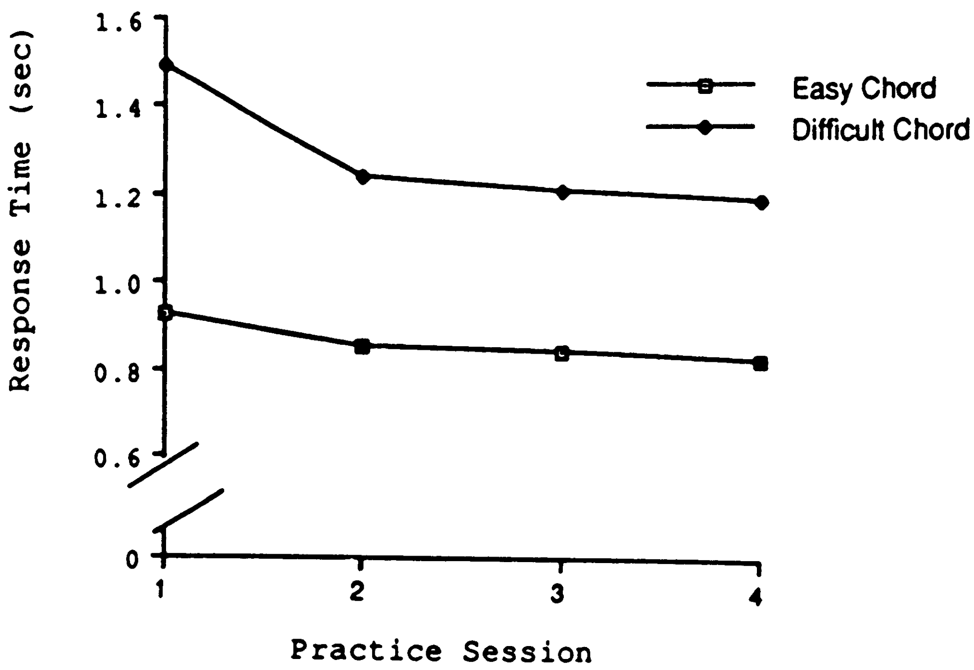


Figure 17. The practice-chord ease interaction effect.

Table 9. Average response times in the practice-chord ease interaction.

Practice Level	Chord Ease Level	Average Response Time (sec)
Session 1	Easy	0.927
	Difficult	1.491
Session 2	Easy	0.841
	Difficult	1.230
Session 3	Easy	0.823
	Difficult	1.195
Session 4	Easy	0.798
	Difficult	1.166

Because of this finding, the two three-way interactions were investigated. In addition, the simple effects of chord ease within each individual practice level were tested. The results of these tests are shown in Table 10.

Table 10. Simple effects of chord ease in practice sessions.

Session	F	p
1	31.23	< 0.01
2	14.86	< 0.01
3	13.63	< 0.01
4	13.30	< 0.01

Although the chord ease effect was significant in all four sessions, the difference in chords is particularly pronounced in session one, decreases sharply in session two, and then procedes through consistently smaller decreases in sessions three and four. This, and a look at the differences between the average response times of chords, across sessions (0.564, 0.389, 0.372, 0.368, respectively), suggests that performance on the difficult chord improves more rapidly than the performance on the easy chord initially, but that a difference between the two chords will persist. This supports the statement made by Seibel (1962b), mentioned earlier, that the response times of the difficult chords may decrease more quickly than the easy chords, but there is always a difference between them.

Practice-Response Repetition-Chord Ease Interaction

This three-way interaction was analyzed to see if the insignificant response repetition-chord ease interaction changed across practice sessions. (The average response times for the levels of this interaction are shown in Appendix D.) The results lead to the inference that it did not ($F(3,30)=0.24$, $p=.8688$).

Practice-Stimulus Quality-Chord Ease Interaction

The insignificant finding from the analysis on this three-way interaction ($F(3,30)=0.82$, $p=.4941$) suggests that the insignificance of the stimulus quality-chord ease interaction does not change across sessions. (The average response times for the levels of this interaction are shown in Appendix E.)

Simple Effects of the Response Repetition-Chord Ease and Stimulus Quality-Chord Ease Interactions in Session Four

Because the analysis of the practice-response repetition-chord ease and practice-stimulus quality-chord ease three-way interactions revealed that the response repetition-chord ease and stimulus quality-chord ease interactions were insignificant throughout the experiment, the simple effects analyses of these two-way interactions in the fourth practice session were not done.

Discussion

The Meaning of the Error Data

The error data revealed that the number of errors is not significantly different across the levels of all the experimental factors except chord ease. The number of errors involving the difficult chord was much greater than the number of errors involving the easy chord. While the consistency in errors across the levels of the other four factors might suggest a consistency in subjects' speed-accuracy tradeoff, the difference in the number of errors across the chord ease levels might suggest a change in their tradeoff. However, the number of errors committed when subjects executed the difficult chord was still relatively small (about 4%), and probably only reflects that this chord was more difficult to execute than the easy chord. The speed-accuracy tradeoff is thus assumed to remain consistent throughout the experiment.

Results That Concur With Hypotheses

Certain results were as predicted by the experimental hypotheses.

As was predicted, there was a significant difference between the response times of error and correct trials, with error trials taking longer. Referring to Swensson's (1972) theory mentioned earlier, this result supports the inference that in this experiment choice discrimination was difficult for subjects, and accuracy was stressed. This second idea is also supported by the small number of errors committed by subjects in the experiment.

The difference between the response times of correct trials that do and do not follow errors was also significant, with trials following errors taking longer. As was mentioned before, this is probably a result of subjects trying to identify the mistake that they had just made, while temporarily ignoring the trial at hand; or, a result of the subjects' concentration being broken by the error beep. (Perhaps in the future a study could be done with some other error feedback.) Therefore, in this study, correct trials that followed errors were excluded from this analysis, because the difference between the response times of correct trials that followed errors were significantly longer than the response times of correct trials that followed correct inputs.

With the hypothesized exception of gender, all main effects (practice, response repetition, stimulus quality, and chord ease) were significant.

Finally, the response repetition-stimulus quality interaction was insignificant. Although this does not prove that the two effects occur in separate stages, it does give some support to the argument that they do. It also lends strength to the idea that the two factors affected their predicted stages. Namely, response repetition affected the chord execution stage, and stimulus quality affected the stimulus encoding stage.

Contradictions To Hypotheses

There were a number of results that did not agree with the hypotheses stated earlier in this paper.

The stimulus quality-chord ease interaction was insignificant, suggesting that a change in the way different chords were cued did not have a different effect on response times. In other words, the cueing scheme does not produce a bigger increase in response time for one chord than another. Further, the two chords represented those that would (easy chord) and would not (difficult chord) benefit from anchor points making their cueing representations more easily recognizable. Because a change in cueing scheme (stimulus quality) did not significantly affect the response times of these chords differently, it can be assumed that the way chords are cued does not cause one chord to have a longer response time than another, and the benefit of having the boxes near anchor points in the cue of the pilot study is not significant.

In applying the Additive Factors Method, it could be said that because of the insignificant interactive effect between stimulus quality and chord ease, the two factors do not occur in the same stage. Thus, the difference in chord response times (chord ease) does not occur in the same stage as a change in cueing scheme (stimulus quality), and therefore the difference in chord response times is not the result of the time it took to encode what they were.

Again, because the null hypothessis (additivity) can never be proven, the results of the stimulus quality-chord ease interaction do not allow one to prove these ideas, they only allow one to suggest that they are true.

The response repetition-chord ease interaction was insignificant throughout the experiment. This indicates that the increase in response times involved in executing the chords twice as opposed to once was not different for the two chords. If this increase in response time represents the movement time of the chords without the effect of visual or mental processing, then it can be said that there is an insignificant difference in the movement time of the two chords. Because these two chords represent the easiest and hardest chords, it might also be said that the movement times of all 64 chords are not significantly different, at least as measured in the pilot study paradigm.

According to the Additive Factors Method, because the response repetition and chord ease effects do not interact throughout the experiment, they do not occur in the same stage. Thus, the difference in chord response times does not take place in the chord execution (movement time) stage, and the difference in chord response times is not due to a difference in chord movement time, at least in the pilot study paradigm. Because the literature states that at least part of the difference in chord response time is due to motor difficulty differences, the pilot study paradigm does not appear to be a useful way of measuring chord ease. The difference in motor difficulty of the chords is either lost or masked in some way within the experimental structure.

The Stage in Which the Difference in Chord Response Times Occurs

Despite the fact that there is a significant difference between the response times of the two chords, this difference does not appear to be caused by visual or motor factors, at least in the present experiment. There are two explanations for this result. First, these factors' effects on response times might have been lost or masked by the pilot study paradigm. This would seem the case, especially for the effect of motor difficulty, since there is strong evidence from the literature that movement time is different for different chords.

Second, it might be that the difference in chord response times was caused by a difference in the time taken for mental processing. This is suggested by the apparent finding that the difference in chord response times does not take place in any of the other stages. It is also supported by Gopher (1986; and Gopher et al., 1985), who found that the mental processing involved in executing chords on his ten key chord keyboard never became automatic, and that it took longer for some chords than others. The subjects always had to go through the process of making the transition from letter, to spatial representation, to finger movements, to actual execution of the chord. This might be true for the TCK, but Gopher states that the motor difference between chords on his keyboard is also responsible for the difference in response times of different chords. Because the paradigm used in the pilot study does not reveal differences in movement time, it should not be used to order chords along the continuum called chord ease.

Conclusion

The results of this experiment reveal that the technique used in the pilot study does not bias chord response time by the way chords were cued. However, the technique also does not expose differences in TCK chord movement time. For this reason, it should not be used as a tool to order chords according to chord ease. While it is possible that chord movement times do not differ, the literature suggests that this is highly unlikely.

This study also suggests that there is a difference in mental processing times for different chords. This possibility should be investigated in future studies.

Suggestions for Future Studies

1. Since it is not certain whether the error beep itself biased the response times of trials that followed errors, a study should be done involving it and other forms of error feedback (visual, etc.), to discover which, if any of them, do not cause such a biasing. If this study reveals that this bias occurs with all forms of error feedback, then the difference between response times of correct trials that do and do not follow errors should be checked, and if it is significant, correct trials that follow errors should be excluded from any larger analysis.

2. The study of the frequency of errors across experimental variables and the comparison of correct and error trial response times is important in understanding the speed-accuracy tradeoff, as well as other factors.

3. The paradigm used in the pilot study should not be used to uncover differences in TCK chord movement times.

4. Since some of the difference in chord response times might occur in the mental processing stages of response time, Donders' Subtraction Method could be used to

find the time involved in these stages for all 64 chords. An ordering of chords according to this value might then be done.

References

Alden, D.G., Daniels, R.W., and Kanarick, A.F. (1972). Keyboard design and operation: review of the major issues. *Human Factors,* 14(4), 275-293.

Allen, M. (1983). Models of hemispheric specialization. *Psychological Bulletin*, 93(1), 73-104.

Armstrong, T.J. (1982). Development of a biomechanical hand model for study of manual activities. In R. Easterby, K.H.E. Kroemer, and D.B. Chaffin, (Eds.), *Anthropometry and biomechanics: theory and application* (pp.183-192). New York: Plenum Press.

Ashby, F.G. (1982). Deriving exact predictions from the cascade model. *Psychological Review,* 89, 599-607.

Baddeley, A.D., and Longman, D.J.A. (1978). The influence of length and frequency of training session on the rate of learning to type. *Ergonomics,* 21(8), 627-635.

Barter, J., Frey, E., and Truett, B. (1956). Anthropometry and biomechanics of the hand. Wright-Patterson Air Force Development Center Aero. Med. Lab., Ohio.

Bartram, D. and Feggou, O. (1985). *A pilot investigation of the sequential keyboard.* (Report ERG/Z6545/85/4a). Hull: University of Hull, Ergonomics Research Group.

Bartram, D., and Lee, M. (1985). *A pilot investigation of the ten-key keyboard.* (Report ERG/Z6545/85/4b). Hull: University of Hull, Ergonomics Research Group.

Brand, P.W. (1985). *Clinical mechanics of the hand.* St Louis: The C.V. Mosby Company.

Briggs, G.E. and Shinar, D. (1972). On the locus of the speed/accuracy tradeoff. *Psychnomic Science*, 28(6), 326-328.

Conrad, R., and Longman, D.J.A. (1965). A standard typewriter versus chord keyboard- An experimental comparison. *Ergonomics*, 8, 77-88.

Cornog, J.R., Hockman, J.F., and Craig, J.C. (1963). Address encoding- A study of the double-binary keyboard as a link in the machine sorting of mail (ASME Report Number 63-WA-338). New York: American Society of Mechanical Engineers.

Donders F.C. (1969). On the speed of mental processes. (Translated by W.G. Koster). *Acta Psychologica*, 30, 412- 431.

Dvorak, A., Merrick, N.F., Dealey, W.L., and Ford, G.C. (1936). *Typewriting behavior: Psychology applied to teaching and learning typewriting*. New York: American Book Company.

Fisher, D.L., Coury, B.G., Tengs, T.O., and Duffy, S.A. (1989). Minimizing the time to search visual displays: the role of highlighting. *Human Factors*, 31(2), 167-182.

Frowein, H.W., and Sanders, A.F. (1978). Effects of visual stimulus degredation, S-R compatability, and foreperiod duration on the choice reaction time and movement time. *Bulletin of the Psychonomic Society*, 12(2), 106-108.

Gatewood, E.L. (1920). Individual finger reactions. *Psychological Monograph*, 28, No. 126 (Whole No.4).

Glencross, D., and Bluhm, N. (1986). Intensive computer keyboard training programmes. *Applied Ergonomics*, 17.3, 191-194.

Gopher, D., and Eilam, Z. (1979). Development of the letter-shape keyboard: a new approach to the design of data entry devices. *In Proceedings of the Human Factors Society 23rd Annual Meeting* (pp.42-44). Santa Monica, CA: Human Factors Society.

Gopher, D., and Koenig, W. (1983). *Hands coordination in data entry with a two-hand chord typewriter* (Technical Report Number CCPL 83-3). Illinois: University of Illinois.

Gopher, D., Koenig, W., Karis, D., and Donchin, E. (1984). *An information processing approach to the effects of representation rules and coordination requirements* (Technical Report Number CPL 84-4). Illinois: University of Illinois.

Gopher, D., Koenig, W., and Karis, D. (1985). The representation of movement schemas in long-term memory: lessons from the acquisition of transcription skill. *Acta Psychologica* 60, 105-134.

Gottsdanker, R., and Shragg, G.P. (1985). Verification of Donders' subtraction method. *Journal of Experimental Psychology: Human Perception and Performance*, 11(6), 765-776.

Hardinski, M., and Pachella, R.G. (1980). The manipulation of stimulus quality and the definition of stimulus encoding operations in memory scanning experiments. *Perception and Psychophysics*, 27(3), 232-240.

Hayes, V., Wilson, G.D., and Schafer, R.L. (1977). Typewriting rate as a function of reaction time. *Perceptual and Motor Skills*, 45, 1179-1184.

Hayes, V., and Halpin, G. (1978). Reaction time of the fingers with responses measured on a typewriter keyboard. *Perceptual and Motor Skills*, 47, 863-867.

Hays, W.L. (1973). *Statistics for the social sciences* (2nd ed.) . New York: Holt, Rinehart & Winston.

Heuer, H. (1982a). Binary choice reaction time as a criterion of motor equivalence. *Acta Psychologica*, 50, 35-47.

Heuer, H. (1982b). Binary choice reaction time as a criterion of motor equivalence: further evidence. *Acta Psychologica*, 50, 49-60.

Heuer, H. (1982c). Choice between finger movements of different and identical form: The effect of relative signal frequency. *Psychological Research*, 44, 323-342.

Heuer, H. (1985). Intermanual interactions during simultaneous execution and programming of finger movements. *Journal of Motor Behavior*, 17(3), 335-354.

Hilgendorf, L. (1966). Information input and response time. *Ergonomics*, 9, 31-37.

Hirsch, R.S. (1970). Effects of standard versus alphabetical keyboard on typing performance. *Journal of Applied Psychology*, 54(6), 484-490.

IBM Corporation. (1986). *Guide to operations : personal computer AT*. Boca Raton, Florida: Author.

Keele, S.W. (1969). Repetition effect: a memory-dependent process. *Journal of Experimental Psychology*, 80(2), 243-248.

Klemmer, E.T. (1958). A ten-key typewriter. (IBM Report Number RC-65). Yorktown Heights, N.Y.: IBM Research Center.

Konheim, A.G. (1981). *Cryptography: a primer*. N.Y: John Wiley and Sons.

Kroemer, K.H.E. (1972). Human engineering the keyboard. *Human Factors*, 14(1), 51-63.

Langley, L.W. (1988). Ternary chord-type keyboard. United States Patent Number 4,775,255.

Litterick, I. (1981). QWERTYUIOP-dinasour in a computer age. *New Scientist*, January, 66-68.

Lockhead, G.R., and Klemmer, E.T. (1959). An evaluation of an 8-key word-writing typewriter. IBM Report Number RC-180. Yorktown Heights: IBM Research Center.

Luce, R.D. (1986). *Response times: Their role in inferring elementary mental organization*. New York: Oxford University Press.

McClelland, J.L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. *Psychological Bulletin*, 86, 287-330.

McCormick, E.J., and Sanders, M.S. (Eds.). (1982). *Human factors in engineering and design* (5th ed.). New York: McGraw-Hill Book Company.

Michales, S.E. (1971). QWERTY versus alphabetic keyboards as a function of typing skill. *Human Factors*, 13(5), 419-426.

Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, 14, 247-279.

Miller, J. and Pachella, R. (1973). On the locus of the stimulus probability effect. *Journal of Experimental Psychology*, 101, 227-232.

Mudd, S. (1983). *Briggs' information-processing model of the binary classification task*. Hillsdale, New Jersey: Lawrence Erlbaum Associates, Publishers.

Nakaseko, M., Grandjean, E., Hunting, W., and Gierer, R. (1985). Studies on ergonomically designed alphanumeric keyboards. *Human Factors*, 27(2), 175-187.

Norman, D.A., and Fisher, D. (1981). *Why alphabetic keyboards are not easy to use: keyboard layout doesn't much matter* (Report Number S108). San Diego: University of California, San Diego.

Noyes, J. (1983a). The QWERTY keyboard: a review. *International Journal of Man-Machine Studies*, 18, 265-281.

Noyes, J. (1983b). Chord keyboards. *Applied Ergonomics*, 14(1), 55-59.

Pashler, H. (1984). Evidence against late selection: Stimulus quality effects in previewed displays. *Journal of Experimental Psychology: Human Perception and Performance*, 10(3), 429-448.

Pieters, J.P.M. (1983). Sternberg's additive factor method and underlying psychological processes: some theoretical considerations. *Psychological Bulletin*, 93(3), 411-426.

Pollatschek, M.A., and Gilad, I. (1984). Keyboards: does use effect its design and layout? Technion-Israel Institute of Technology, Report submitted to *BYTE*, December, 1984.

Rabbitt, P.M.A, Vyas, S.M., and Feamley, S. (1975). Programming sequences of complex responses. In: P.M.A. Rabbitt and S. Dornic (Eds.), *Attention and Performance V* (pp.395-416). New York: Academic Press.

Raji, D., Gopher, D., and Kimchi, R. (1987). Perceptual and motor determinants of efficient data entry. In *Proceedings of the Human Factors Society 31st Annual Meeting* (Vol.2) (pp.820-824). Santa Monica, CA; Human Factors Society.

Ratz, H.C., and Ritchie, D.K. (1961). Operator performance on a chord keyboard. *Journal of Applied Psychology*, 45(5), 303-308.

Richardson, R.M.M, Telson, R.V., Koch, C.G., and Chrysler, S.T. (1987). Evaluation of conventional, serial, and chord keyboard options for mail encoding. In *Proceedings of the Human Factors Society 31st Annual Meeting* (Vol. 2) (pp. 911-915). Santa Monica, CA: Human Factors Society.

Rochester, N. Bequaert, F.C., and Sharp, E.M (1987). The chord keyboard. *Computers*, 11(12), 57-63.

Rumelhart, D. and Norman, D. (1982). Simulating a skilled typist: A study of cognitive motor performance. *Cognitive Sciences*, 6, 1-36.

SAS Institute Inc. (1985). *SAS user's guide: statistics.* Cary, NC: SAS Institute Inc.

Seibel, R. (1962a). Performance on a five-finger chord keyboard. *Journal of Applied Psychology*, 46(3), 165-169.

Seibel, R. (1962b). Discrimination reaction time as a function of the number of stimulus-response pairs and the self-pacing adjustment of the subject. *Psychological Monographs*, 76 (42, Whole No.561).

Seibel, R. (1963). Discrimination reaction time for a 1,023-alternative task. *Journal of Experimental Psychology*, 66(3), 215-226.

Seibel, R. (1972). Data entry devices and procedures. In Van Cott, H., and Kinkade, R. (Eds.), *Human engineering guide to equipment design* (pp. 311-345). Washington DC: American Institute for Research.

Seigel, S. (1956). *Nonparametric statistics for the behavioral sciences.* New York: McGraw Hill Book Company.

Sheridan, M.R. (1981). Response programming and reaction time. *Journal of Motor Behavior*, 13(3), 161-176.

Shwartz, S.P., Pomerantz, J.R., and Egeth, H.E. (1977). State and process limitations in information processing: an additive factors analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 3(3), 402- 410.

Sidorsky, R.C. (1974). ALPHA-DOT: a new approach to direct computer entry of battlefield data (Technical Report Number 249). Arlington, Virginia: U.S Army Research Institute for Behavioral and Social Sciences.

Smith, E.E. (1968). Choice reaction time: An analysis of the major theoretical positions. *Psychological Bulletin*, 69, 77-110.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, 30, 276-315.

Swanson, J.M., and Briggs, G.E. (1969). Information processing as a function of speed versus accuracy. *Journal of Experimental Psychology*, 81, 223-229.

Swensson, R.G. (1972). The elusive tradeoff: Speed versus accuracy in visual discrimination tasks. *Perception and Psychophysics*, 12, 16-32.

Taylor, D.A. (1976). Stage analysis of reaction time. *Psychological Bulletin*, 83(2), 161-191.

Theios, J. (1973). Reaction time measurements in the study of memory processes: Theory and data. In G.H. Bower (Ed.), *The psychology of learning and motivation* (Vol.7) (pp.43-85). New York: Academic Press.

Townsend, J.T. (1984). Uncovering mental processes with factorial experiments. *Journal of Mathematical Psychology*, 28, 363-400.

Van Nes, F.L. (1976). Analysis of keying errors. *Ergonomics*, 19(2), 165-174.

Vickers, D. (1979). *Decision processes in visual perception*. London: Academic Press.

Welford, A.T. (1980). Choice reaction time: Basic concepts. In A.T. Welford (Ed.), *Reaction times*. (pp.73-128). New York: Academic Press.

Wickens, C.D. (1984). *Engineering psychology and human performance*. Boston: Scott, Foresman, and Company.

Winer, B.J. (1971). *Statistical principles in experimental design* (2nd ed.). New York: McGraw-Hill Inc..

Appendix A. CONSENT FORM

I, ______________________________ am participating in this research study because I want to. The decision to participate is completely voluntary on my part. No one has coerced or intimidated me to participate.

The experimenter has adequately answered any and all questions I have asked about this study, my participation, and the procedures involved, which are described in the attached "EXPERIMENT INSTRUCTIONS," which I have initialled.

I recognize the Principal Investigator as Thomas F. Callaghan (231-5359).

I understand that he will be available to answer any questions concerning procedures throughout this study. I understand that if significant new findings develop during the course of this research which may relate to my decision to continue participation, I will be informed. I further understand that I may withdraw this consent at any time and discontinue further participation in this study without prejudice to my entitlements. I also understand that the Principal Investigator, his assistants, or a medical consultant for this study may terminate my participation in this study if he or she feels this to be in my best interest. I may be required to undergo certain further examinations, if they are necessary for my health or well- being.

I do not have any disorders of my cardiovascular system, of my spinal column (particularly in the lower back), or any other disorders or deficiencies, which make it unadvisable for me to participate in this experiment.

I understand that in the case of physical injury no medical treatment or compensation are offered under the research program, or by VA Tech-VPI.

I understand that for my participation I shall receive payment in the amount of $5 per hour, and also that if I withdraw from the experiment before it is completed, I will be paid only for the time I actually spent performing in the experiment.

I understand that the results of my efforts will be recorded and that I may be photographed, filmed, or audio/videotaped. I consent to the use of this information for scientific or training purposes, and I understand that any records of my participation in this study may be disclosed only according to federal law, including the Federal Privacy Act, and its implementing regulations. This means that personal information will not be released to an unauthorized third party without my permission.

I understand that if I have any further questions about my rights as a participant, I may contact Dr. Ernest R. Stout, Chairman of the Institutional Review Board at VPI&SU, at 231-5281.

I FULLY UNDERSTAND THAT I AM MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. MY SIGNATURE INDICATES THAT I HAVE DECIDED TO PARTICIPATE UNDER THE CONDITIONS DESCRIBED ABOVE.

Signature	Date
Printed name	SS number
	Phone Number
Address	

Appendix B. EXPERIMENT INSTRUCTIONS

The purpose of this study is to gather information about a newly designed keyboard, called the Ternary Chord Keyboard (TCK).

This keyboard has only eight keys. Each key is assigned to one of your eight fingers (there are no keys for your thumbs). You should keep each finger on its assigned key at all times. The keys have three positions: forward, neutral, and backward. When using this keyboard, two fingers (one from each hand) will activate their assigned keys simultaneously. This simultaneous activation of two keys is called a chord.

The experiment will be divided into four sessions. Within each session there will be two blocks. In the single execution block, your task will be to execute a chord once in response to a cue. In the double execution block, you will have to execute a chord two times in succession in response to a cue. The experimenter and the computer screen will identify the block you are about to begin.

The chord you should execute will be shown on the computer screen by a horizontal row of eight boxes. Each box will represent one of the eight keys on the keyboard. The relationship between the boxes and the keys is such that the box on the left end of the row represents the left little finger key, and the box on the right end of the horizontal row represents the right little finger key.

You will move the two keys whose boxes are displaced from the horizontal row. Each of these two boxes will be displaced either up or down. If the box is displaced up, you will move the key it represents forward. If the box is displaced down, you will move the key it represents backward. The displaced box will be shaded in some circumstances, and unshaded in others. (The experimenter will show you examples of these cueing strategies.)

If you execute an incorrect chord, a beep will sound. In the block in which you must execute chords twice in response to one cue, a beep will sound (after the second execution) if the first execution is wrong, the second execution is wrong, or both executions are wrong.

Whether you execute the correct chord or an incorrect one, a new chord will be cued and you will move on. In other words, you will not have a chance to correct mistakes. For this reason, do not dwell on them.

Please work both ACCURATELY and QUICKLY.

If you have any questions, please ask the experimenter at this time.

Initials ______

Appendix C. Statistical Model

Between Subjects	**df**
G	1
S(G)	10

	11

Within Subjects	**df**		**df**		**df**
P	3	S*G	3	P*S(G)	30
R	1	B*G	1	R*S(G)	10
P*R	3	P*R*G	3	P*R*S(G)	30
Q	1	Q*G	1	Q*S(G)	10
P*Q	3	P*Q*G	3	P*Q*S(G)	30
R*Q	1	R*Q*G	1	R*Q*S(G)	10
P*R*Q	3	P*R*Q*G	3	P*R*C*S(G)	30
C	1	C*G	1	C*S(G)	10
P*C	3	P*C*G	3	P*C*S(G)	30
R*C	1	R*C*G	1	R*C*S(G)	10
P*R*C	3	P*R*C*G	3	P*R*C*S(G)	30
Q*C	1	Q*C*G	1	Q*C*S(G)	10
P*Q*C	3	P*Q*C*G	3	P*Q*C*S(G)	30
R*Q*C	1	R*Q*C*G	1	R*Q*C*S(G)	10
P*R*Q*C	3	P*R*Q*C*G	3	P*R*Q*C*S(G)	30

					372
			Total =	383	

Subject(S)	Gender(G)	Response Repetition(R)
Stimulus Quality(Q)	Practice(P)	Chord(C)

Appendix D. Average Response Times of Practice-Response Repetition-Chord Ease Interaction

Practice Level	Response Repetition Level	Chord Ease Level	Average Response Time
Session 1	Easy	Difficult	1.347
Session 1	Easy	Easy	0.779
Session 1	Difficult	Difficult	1.635
Session 1	Difficult	Easy	1.076
Session 2	Easy	Difficult	1.068
Session 2	Easy	Easy	0.689
Session 2	Difficult	Difficult	1.391
Session 2	Difficult	Easy	0.993
Session 3	Easy	Difficult	1.030
Session 3	Easy	Easy	0.672
Session 3	Difficult	Difficult	1.360
Session 3	Difficult	Easy	0.974
Session 4	Easy	Difficult	0.998
Session 4	Easy	Easy	0.654
Session 4	Difficult	Difficult	1.334
Session 4	Difficult	Easy	0.942

Appendix E. Average Response Times of Practice-Stimulus Quality-Chord Ease Interaction

Practice Level	Stimulus Quality Level	Chord Ease Level	Average Response Time
Session 1	Easy	Difficult	1.470
Session 1	Easy	Easy	0.921
Session 1	Difficult	Difficult	1.512
Session 1	Difficult	Easy	0.934
Session 2	Easy	Difficult	1.200
Session 2	Easy	Easy	0.813
Session 2	Difficult	Difficult	1.259
Session 2	Difficult	Easy	0.868
Session 3	Easy	Difficult	1.190
Session 3	Easy	Easy	0.806
Session 3	Difficult	Difficult	1.201
Session 3	Difficult	Easy	0.840
Session 4	Easy	Difficult	1.155
Session 4	Easy	Easy	0.763
Session 4	Difficult	Difficult	1.177
Session 4	Difficult	Easy	0.833

The vita has been removed from the scanned document