Observation, Description, and Prediction of Long-Term Learning on a Keyboarding Task

by

Mark L. McMulkin

Thesis Submitted to the Faculty of the Virginia Polytechnic Institute and State University in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Industrial and Systems Engineering

APPROVED:

K.H.E. Kroemer, Chairman

R.C. Williges

J.C. Woldstad

Blacksburg, Virginia

January, 1992
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Mark Lee McMulkin

Committee Chairman: Karl H. E. Kroemer

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(ABSTRACT)

Three major principles of learning a chord keyboarding task were investigated. Five subjects were taught 18 characters on a chord keyboard, then practiced improving their keying speed for about 60 hours.

The first objective of the study was to observe long-term learning on a keyboarding task. The performance, in characters typed per minute, was recorded over the entire range of the experiment. Typing skill improved quickly in the beginning and then slowed, but performance had not reached a stable peak by the end of the experiment.

The second objective of this study was to determine a function that describes performance progress from initial training to a high keying speed. Five functions were evaluated; a function which predicts the logarithm of the dependent variable (characters per minute) from the logarithm of the regressor variable provided a good fit to the actual data. The final form of the equation was $\text{CPM}_i = e^{B_0T_iB_1}$, where $\text{CPM}_i =$ performance in characters per minute on the $i$-th interval, $T_i =$ the $i$-th interval of practice, and $B_0$ and $B_1$ are fitted coefficients.

The second objective also considered the form that $T_i$ (from the above equation) should take. Performance can be predicted from number of
repetitions such as trials, or from amount of practice such as hours. Both trials and time were used as predictor variables and both provided equally accurate predictions of typing speed. Both also provided excellent fits in conjunction with the Log-Log equation. Thus, it appears the Log-Log function is fairly robust in predicting performance from different variables.

The third objective was to investigate how many trials of performance are needed before the entire learning function can be reasonably determined. In this experiment, subjects practiced for an extended period of time (about 60 hours) so a fairly complete progression of performance could be gathered. Yet, it would be more convenient to collect data for only a few hours and deduce the ensuing performance of the subject. The coefficients of the Log-Log function were determined using only the first 25, 50, 100, 150, and 200 of the initial performance points (out of about 550 total actual data points). The mean squared error (MSE) was calculated for each of these fits and compared to the MSE of the fit using all points. It appears that at least 50 performance data points are required to reduce the error to a reasonably acceptable level.
ACKNOWLEDGEMENTS

This work was possible due to the funds and facilities provided by the Center for Innovative Technology (CIT) of Virginia, the Department of Industrial and Systems Engineering, in particular, the Industrial Ergonomics Laboratory, and Vatell Corporation.

I would like to extend my appreciation and thanks to my committee chair, Dr. Karl Kroemer, for his encouragement, assistance, time, and support throughout this project and my entire Masters Degree education. I would also like to thank my other committee members, Dr. Jeff Woldstad and Dr. Robert Williges, for their advice and guidance on this project which were instrumental to the completion of this thesis.

Finally, I would like to thank my fellow graduate students for their help during my thesis, particularly Chris Rockwell for his assistance in troubleshooting the experimental set-up.
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1. INTRODUCTION

1.1 The One-Hand Ternary Chord Keyboard.

The keyboard is currently the primary device which people use for data input to, and interaction with, a computer. The accepted keyboard standard is the QWERTY keyboard (named for the first six keys on the left side of the second row). Chord keyboards have been proposed as an alternative device to the QWERTY keyboard. A chord is defined as the simultaneous activation of two or more keys to produce one input. Although many differences exist between various chord and sequential keyboards, almost all use binary keys. The binary key has only two states: on and off. An example of a binary key is the type of key used on the standard QWERTY keyboard.

A new type of chord keyboard has been designed by VATELL Corporation, Christiansburg, Virginia (U.S. Patent 4,775,255 of October, 1988). This keyboard, called the Ternary Chord Keyboard (TCK), uses keys which have three states: two on and one off. Figure 1 shows a comparison of the binary and ternary keys. The TCK uses the three-position ternary keys, whereas all previous keyboards have used the two-position binary keys. The TCK, discussed in detail in section 2.5, is intended to be used by two hands (eight keys one for each finger) for data entry of the alphabet, numbers, punctuation, symbols, and cursor keys. Each of 64 "simple" chords is generated by activating one key with the left hand and one key with the right hand. Several authors have analyzed the TCK for performance compared to the QWERTY keyboard, learning times, and performance capabilities (Fathallah, 1988;
(a) Binary Key

Key Activation
(finger pushes downward)

(State 1, no input)
Neutral

(State 2, input 1)
Downward

(b) Ternary Key

Key Activation
(finger pushes forward or pulls backward)

(State 1, no input)
Neutral

(State 2, input 1)
e.g., backward

(State 3, input 2)
e.g., Forward

Figure 1. View of Binary and Ternary Keys
Callaghan, 1989; Kroemer, 1990). All of these experiments investigated the use of a two-hand TCK as an alternative to the QWERTY keyboard.

Many data computation and entry tasks only require the use of a numerical keypad. Numerical keypads require only 18 distinct characters (i.e., the numerals 0 to 9, "plus", "minus", "divide", "multiply", "decimal point", "backspace", "subtotal", and "total"). A chord on the one-hand TCK is defined as the activation of two keys by two different fingers on the same hand. (This is different from the two-hand TCK in which one finger is used from both hands to generate a chord.)

A total of 24 simple chords (those generated by two fingers) are possible on the one-hand TCK. McMulkin and Kroemer (1991) and Lee and Kroemer (1991) determined subjective ratings for ease of activation, response times, and fastest possible keying capabilities for all 24 chords on the one-hand TCK. The characters (numbers and functions) used for a numeric keypad were then assigned to the 18 "best" chords of the one-hand TCK.

1.2 Rationale.

When considering how people learn to use keyboards, several questions arise. First, what is the “learning curve” to reach peak performance? In other words, how does performance progress, how long does it take to reach maximum keying rate, and how fast does a person type after a certain number of hours using a keyboard? Second, what is the maximum speed a person can type using a particular keyboard (maximum speed being the point where the rate of typing stops to increase significantly)? Finally, how can it be judged when peak performance has been reached, and what criteria should be used to
assess performance/skill? Prior research on keyboard use has concentrated primarily on finding the maximal performance and ignored the rate of progress to reach final speed and the criteria on which to predict speed.

The term "learning curve" is often used when discussing keyboarding tasks. For the purposes of this study, learning curve is defined as the way in which a subject's performance progresses or improves over a period of time or number of trials. The term learning curve is not intended to mean that there is one equation that describes the way in which people learn all skills.

The QWERTY keyboard has been in use for over 100 years, yet surprisingly few studies have been conducted to establish learning curves. Naturally, with the number of people that use the QWERTY keyboard, maximal typing speeds have been reported, but the criteria (time or number of characters typed) used to indicate performance progress to top speed have not been studied.

As alternative keyboard designs are investigated, the main thrust of experimentation is to compare the performance of the new design with the QWERTY design. In most reported experiments, subjects using the new keyboard did not achieve peak performance (peak performance being the fastest attainable keying speed); however, the experimenters compared performance between the new keyboard and QWERTY keyboard at equivalent points in learning. For example, Bowen and Guinness (1965), in evaluating a mail sorting task, stated that after 25 hours of training, people using a chord keyboard sorted 30 letters per minute while people using a QWERTY typewriter sorted 33 letters per minute. There was no discussion of how performance progressed during those 25 hours. No indication was given that "hours of
training" was the best criterion to evaluate speed; perhaps, "number of characters typed" would be a better measure.

This study examined the performance progress of subjects on the one-hand TCK. The subjects were taught 18 chords. After learning the chords, the subjects practiced using the one-hand TCK for an extended period of time, 60 hours, so that they approached maximal keying speed.

1.3 Experimental Purpose and Objectives.

This study had the following primary experimental objectives:

1. Investigate the performance progress of people on the one-hand Ternary Chord Keyboard as they attain peak keying speed.

2. Find a function which accurately predicts the learning or progress of the subjects. Evaluate a set of criteria to find which can be used to best predict a subject's performance in keyboarding. The criteria sets are:
   1) The number of hours a person spends practicing.
   2) The number of trials or characters typed.
   3) Subjects' opinion of when they have reached peak performance.

3. Determine the number of initial performance data points that are needed to predict the entire learning function.
2. LITERATURE REVIEW

2.1 Overview of Keyboard Design.

The first keyboard that used the QWERTY layout was designed and produced in 1874. Several attempts have been made to improve this design. Many of the alternative designs have been concerned with rearranging the keys. The most famous of these are the Dvorak keyboard (named for the inventor August Dvorak, not for the arrangement of the keys) and the alphabetic layout (Noyes, 1983b).

Other alternative designs have employed chords (simultaneous activation of two or more keys to produce one input) to enter data. Colombo was the first to attempt to develop a mechanical chord keyboard in 1942 when he requested a patent (Noyes, 1983a). Since that time, many other chord keyboards have been proposed and tested (Gopher and Raij, 1988; Richardson, Telson, Koch, and Chrysler, 1987; Gopher, 1986; Kirschenbaum, Friedman, and Melnik, 1986; Gopher, Hilsenhath, and Raij, 1985; Bartram and Feggou, 1985; Mussin, 1980; Gopher and Eilam, 1979; Rochester, Bequaert, and Sharp, 1978; Sidorsky, 1974; Bowen and Guinness, 1965; Conrad and Longman, 1965; Cornog, Hockman, and Craig, 1963; Seibel, 1962; Ratz and Ritchie, 1961; Lockheed and Klemmer, 1959; Klemmer, 1958). These keyboards involved different numbers of keys, required the use of one hand or both hands, and used different numbers of fingers to activate a chord.

The literature on various keyboards will be reviewed for information relevant to the objectives of this study. Emphasis will be given to studies evaluating performance progress during a keyboarding task and the criteria
used to evaluate learning. Several studies have been conducted in which only final performance on the keyboard is listed with little regard for the way it was attained (e.g. performance at hourly increments). These will be reviewed because they provide some insight to the objectives of this experiment. The important variables that needed to be considered for this study will be discussed.

2.2 The QWERTY Keyboard.

The typewriter has changed significantly from its first design in 1874. It began as a manual entry device in which the human fingers generated the force to move the typebars which struck the paper. The next major evolutionary advancement in typing was the advent of the electric typewriter. The fingers still activated the keys, but an electric motor generated the force to actuate the typebars (or some other device to print characters on paper). Now, computer word processing is replacing the conventional typewriter; keys are still activated by the fingers, but electrical impulses generate the characters on a CRT to be printed later on paper. Through all these mechanical and electrical changes one element of data entry has remained essentially the same - the layout of the characters on the keyboard.

Since the layout of the keys has not changed much since its invention, the ability of people to learn the location of the characters and attain peak performance should not have changed much either. However learning curves for the QWERTY keyboard are not well documented. In the early 1900's, several schools existed that taught students to type. Three of these schools
documented speed progress to improve teaching methods. These three studies will be reviewed (Chapman, 1919; Thurstone, 1919; and Green, 1940).

2.2.1 Chapman (1919).

The purpose of Chapman's (1919) study was to observe the rate of typing improvement of high school students. The number of characters taught to the subjects was approximately 65. Although this was not explicitly stated, subjects were taught to use the typewriter; the early typewriters probably contained between 60 and 70 characters. He administered a five-minute typing test to 20 students once a week; the tests were not begun until the students had completed 20 hours of practice time to learn the keyboard. Every week, for each student, the author recorded hours practiced (both in and out of school), gross number of words typed during the five-minute test, and number of errors. The author then plotted average net words per minute typed (gross words per minute minus the number of words with errors) versus practice time for 20 to 180 hours. Chapman (1919) found the following results: 1) an initial linear learning relationship existed for the first 75 hours, 2) the slope of the learning curve abruptly changed at 90 hours of practice; the rate of learning was six times as large between 20 to 90 hours as it was between 90 to 180 hours, 3) at 180 hours of practice the curve was nearly flat which indicates the students were at nearly peak performance (48 words per minute or 240 characters per minute were actually reached). Figure 2 shows the learning curve that Chapman (1919) obtained. Note that the curve shown is the average over all 20 students; it is not for a single subject.
One problem with this study is that the practice time between tests for each student was not kept constant. For example, subject A may have practiced eight hours in week five, while subject B practiced only three hours during that week; yet, the same test was administered to both subjects at the same time. This problem left unequal sample sizes at each interval of time, as well as different subjects’ data at each time.

An interesting result of this study was that subjects reached peak performance in about 180 hours (although practice on each character is not equivalent). Another important note is that the author related performance to hours of practice. No other practice criterion was measured, such as pages typed.

2.2.2 Thurstone (1919).

Fifty-one students learning to type at a business school were tested for typing speed once a week for 28 consecutive weeks. Students practiced 10 hours a week (2 hours daily). At the end of each week, Thurstone (1919) gave a test to measure the number of words typed over four minutes. Words typed per four minutes were plotted as a function of total practice pages typed. The author fit a curve to the data which yielded the following equation: \( y = \frac{216(x+19)}{(x+148)} \), where \( y \) was average words typed in four minutes and \( x \) was number of pages of practice. The above equation predicted a maximum typing speed of 54 words per minute (WPM) or 216 words in four minutes (as shown in Figures 3 and 4) after over 1000 pages of practice. Subjects actually reached an average of 41 WPM (205 characters per minute, CPM) after about 250 pages of
Figure 3. Learning Curve for a QWERTY Keyboard Found by Thurstone (1919)
Predicted by Number of Pages Typed
Figure 4. Learning Curve for a QWERTY Keyboard Found by Thurstone (1919)
Predicted by Number of Weeks of Practice
practice. The entire learning curve for performance versus pages typed is shown in Figure 3. This curve is the average over all subjects.

Thurstone (1919) then plotted words typed in four minutes versus weeks of practice (about 10 hours of practice per week for 28 weeks), see Figure 4. This plot yielded a curve which was treated as a third order polynomial, whereas the plot of WPM versus pages of practice was described as a second order polynomial by Thurstone (1919).

This study suffers from the same constraints as Chapman's (1919). The tests were administered to all subjects at the same time, but the subjects were at different levels of practice (number of pages typed). It is interesting to note that the shape of the learning curve changes from second to third order when the criterion to judge performance was changed from pages typed to weeks (hours) of practice. This might be due to the fact that the pages typed per hour increased over the 28 weeks.

2.2.3 Green (1940).

Green (1940) studied the typing progress of students over one semester of classes. There were four groups of students: those in first semester typing, those in second semester typing (who had already taken typing in the first semester), those in third semester typing (who had already taken typing in the first and second semesters), and those in fourth semester typing (who had already taken typing in the first, second, and third semesters). Progress was only recorded for one semester; therefore, for example, the learning curve for the first three semesters of the fourth semester students was not known. Speed tests were administered to the subjects once a week for 18 weeks.
Students in the fourth semester reached a peak speed of about 47 WPM at week 18. This was presumably after a total of about 360 hours of practice (18 weeks X 5 hours/week X 4 semesters). The rate of learning (slope of the learning curve) became flatter from the first to the fourth semester, see Figure 5.

A concern with this study is that four different groups of people are used for different sections of the learning curve. This made it difficult to track performance progress from start to finish. Also, WPM was plotted as a function of weeks of practice; this was a fairly coarse measure, considering how much practice time could vary between subjects in a week's time.

2.3 Alternative Layouts of the Standard Keyboard.

The most famous attempts to change the QWERTY layout have been the Dvorak keyboard named for its inventor, August Dvorak, and the alphabetic layout (Noyes, 1983b); the most common alphabetic layout had the letters arranged with ABCDEFGHIJ on the second row, KLMNOPQRST on the third row, and VWXYZ on the bottom row, although other alphabetic layouts existed (Norman and Fisher, 1982). While neither of these designs has experienced commercial success, studies have been conducted to compare the performance of alternative designs to the QWERTY layout. The majority of the papers published on alternative layouts present theoretical arguments for the advantages of one layout over the other. The one paper found that employed experimentation to assess performance of subjects using an alternative keyboard will be discussed.
Figure 5. Median Speed for Four Semesters of Typewriting on a QWERTY Keyboard. Adapted from Green (1940).
2.3.1 Strong (1956).

In an experiment to evaluate the Dvorak layout, Strong (1956) retrained ten typists to use the Dvorak keyboard. They were trained on the new keyboard until they had reached the original speed they had possessed on the QWERTY keyboard. The time to retrain the subjects was recorded in number of hours and was largely a function of original speed; the faster the original speed the longer the retraining. Once the subjects had been retrained on the Dvorak keyboard, ten additional subjects using the QWERTY keyboard were added to the experiment who had roughly the same typing speed as the Dvorak group. Both groups were then given an additional 100 hours of training. Over the final 100 hours of training the QWERTY group improved from an average of 61.7 WPM to 81.7 WPM (on a five minute typing test), a 20 WPM improvement. The Dvorak group improved from an average of 54.9 WPM to 66.2 WPM (on a five minute typing test), an 11.3 WPM improvement. Overall the QWERTY group improved 8.7 WPM more (20 WPM improvement minus 11.3 WPM improvement) than the Dvorak group. No further conclusions could be drawn from this experiment. Although the Dvorak keyboard has been a popular alternative to the QWERTY keyboard, no other experiments were found which compared it to the QWERTY keyboard. Therefore, no further conclusions can be drawn for this study.

2.4 Binary Chord Keyboards.

A variety of chord keyboards have been investigated which differ in aspects such as number of keys used, number of fingers used to generate a chord, and character set size. For each of the following studies, how the
keyboard worked will be briefly described, as well as performance results obtained.

2.4.1 Klemmer (1958).

One of the first documented experiments on a chord keyboard was performed by Klemmer (1958) on a ten-key chord keyboard (one key for each digit). Two subjects were taught a set of 30 characters (26 letters, "space", "return", "period", and "comma"). Ten characters were generated with one finger, nine with two fingers of the same hand, and eleven with one finger from each hand. Klemmer (1958) had the subjects repeatedly type 17 different text sets which consisted of 60 words drawn from a list of the 1000 most frequent words in English. The subjects typed the word sets for approximately 35 hours (50 minutes a day, 3 times a week for 12 weeks); one subject improved from 20 WPM to 60 WPM (went 19 times through the group of 1020 words), while the other went from 17 WPM to 37 WPM (12 times through the 1020 words). Learning curves, Figure 6, were generated as WPM versus number of times through the group of 1020 words. Trends in the curves are difficult to extract. For an additional six hours, subjects typed samples of text containing about 670 characters. The first subject consistently averaged about 47 WPM while the second averaged about 30 WPM.

A relation between size of character set and amount of practice time to high performance can be inferred by comparing this study to the studies by Chapman (1919), Thurstone (1919), and Green (1940). Klemmer (1958) taught 30 characters and reached around 45 WPM (225 CPM) in approximately 35
Figure 6. Typing Speed on a 10-Key Chord Keyboard as a Function of Practice. Taken from Klemmer (1958).
hours. Chapman (1919), Thurstone (1919), and Green (1940) taught about 65 characters and did not reach 45 WPM (225 CPM) until 160 to 300 hours.

2.4.2 Lockheed and Klemmer (1959).

A chord keyboard using eight keys, one for each finger, was developed by Lockheed and Klemmer (1959). Chords were generated by simultaneous activation of one to eight keys. Lockheed and Klemmer began by teaching four subjects the chord patterns for 100 words. On the average, subjects took 20 hours to learn the 100 word patterns. Subjects then learned the 26 letters of the alphabet and the 10 numerals; it took an additional six hours to learn the 36 new characters and integrate them with the original 100 word patterns. The subjects then typed text (for about two hours) which contained approximately an equal number of words which were in the 100 word pattern chords and words which had to be typed one letter at a time. Subjects averaged about 15 WPM (or 45 chords entered per minute, \([15/2]X2 + 15/2\), as estimated by the author of this paper).

This study used a considerably larger chord/character set than the other experiments that are reviewed. Long training times and low chords per minute are expected with such a large set of chords. The chords entered per minute are difficult to interpret because all the data are reported as WPM. Lockheed and Klemmer (1959) guessed that the upper limit of speed for chords using three fingers or more is 120 chords per minute. Single finger key activations were estimated to have an upper speed of 300 key entries per minute. However, they gave no indication as to the length of training time required to reach these limits.
2.4.3 Ratz and Ritchie (1961) and Seibel (1962).

Ratz and Ritchie (1961) and Seibel (1962) used the same one-hand five-key chord keyboard. A total of 31 chords were possible using 1, 2, 3, 4, or 5-finger combinations. The chord to be activated was presented on a display of five lights that corresponded to the five keys. Both studies measured the response time of all 31 chords (time from onset of light pattern to activation of all of the corresponding keys). Ratz and Ritchie obtained an average response time of 1.2 seconds after 2,660 measured response times. Seibel found an average response time of about 0.32 seconds after 11,000 response times. The large difference in response times was assumably due to more practice in Seibel's experiment. In fact, Seibel (1962) performed the study to show that Ratz and Ritchie (1961) had not attained the shortest response times possible. These response times do not indicate training periods to reach maximum performance on a typing task, but they indicate the approximately fastest keying rate attainable when there are 31 choices.

2.4.4 Cornog, Hockman, and Craig (1963).

Cornog et al. (1963) experimented with a chord keyboard for sorting mail that had 12 keys (2 rows of 6) for each hand, two keys for each finger and four keys for the thumb. Each hand, on its own, could generate all 26 letters and 10 numbers (each hand operated an independent keyboard). Twelve characters could be entered by activating one key while the remaining 24 required the depression of two keys (from the same hand) simultaneously. The authors trained subjects for one-and-a-half hours a day for 11 weeks, a total of about 80
hours until they reached "moderate" proficiency; the authors do not elaborate on how proficiency was determined or what "moderate" means. For the next 15 weeks, the subjects performed sorting on an outgoing mail task. No learning curves of progress performance were reported; however average performance at the end of 15 weeks was 232 characters per minute (CPM). For weeks 16 to 30 the subjects performed an incoming mail sorting task. Typing speed at the end of week 30 was an average of 180 CPM. Finally, during weeks 31 to 36, subjects performed an originating mail sorting task. At the completion of week 36, average typing speed was 170 CPM.

Subjects received a considerable amount of practice using the chord keyboard (estimated at least 300 hours). However, they were learning a very difficult task. First, they had to learn 36 character chords for each hand. Second, they had to learn the coding schemes to sort mail, i.e., what letters and numbers to enter for each address. The task of the subjects was to read the address on the letter, determine the code that needed to be entered on the keyboard, recall the chords needed to produce the code, and then enter those chords. Therefore, it is difficult to separate the portion of practice attributable to learning the keyboard from the portion of time attributed to learning to read and code addresses. Also, the average CPM at the end of each section of practice was confounded with the type of task - outgoing, incoming, or originating mail. However, it appears that highest performance, 232 CPM, was found before the task was changed at the end of 11 weeks of training and an additional 15 weeks of practice - a total of about 190 hours.
2.4.5 Conrad and Longman (1965).

An experiment to compare the standard typewriter with a chord keyboard was conducted by Conrad and Longman (1965) for the British post office. The chord keyboard was comprised of 12 keys, six for each hand. Letters and numbers, a total of 36 characters, were generated by pressing two keys, one by each hand. An additional five keys were used for the functions of enter, cancel, and coding of local addresses. Subjects participated in the experiment for 3 1/2 hours a day, 5 days a week for 7 weeks. One group of 24 subjects learned the 36 characters on the standard typewriter, while another group of 22 subjects was taught the chord keyboard.

The intent of the study was to compare relative performance of the two keyboards at stages along the learning curve, not to find the maximum performance possible in seven weeks of practice. However, the learning curves and method are pertinent to the objectives of this study.

The group trained on the chord keyboard became "operational" in an average of 12 days, while the typewriter group needed an average time of 21 days; "operational" was defined as the subjects being able to type all 36 characters accurately as determined by the instructor. The typewriter group became "operational" an average of 9 days slower than the chord group. After learning the characters, the two groups practiced to increase speed for the remainder of the 35 days. Figure 7 shows the learning curves for both groups as a function of days. Performance on each day was an average of four speed tests across all subjects that were considered operational by that day. It is important to note that the performance curves begin earlier for the chord group because its members were operational earlier. When the typewriter group was
Figure 7. Comparison of Typing Speeds for Chord and QWERTY Keyboards. 
Taken from Conrad and Longman (1965).
added to the graph, it was consistently slower than the chord group. It should also be pointed out that at the end of training, after 120 total hours, typing speed had reached almost 100 CPM for the chord group and was still increasing approximately linearly. However, each day represented three hours of training so it is difficult to interpret the utility of each hour.

An editorial note: the training schedules in the studies differed significantly. For example, Klemmer (1958) trained subjects for one hour a day while Conrad and Longman (1965) had subjects practice nearly four hours a day. Massed or distributed training can have profoundly different effects on performance (Goldstein, 1986); this aspect will be covered in greater detail later (section 2.6). In reviewing each of the studies, caution should be used in relating total hours of practice to final performance because the method to reach that total number of hours may drastically affect performance.

2.4.6 Bowen and Guinness (1965).

Bowen and Guinness (1965) designed another experiment investigating the differences between chord and standard keyboards in a mail sorting task. Three keyboards were investigated: a standard typewriter, a large chord keyboard (12 keys for each hand), and a small chord keyboard (6 keys for each hand). Subjects learned 11 keying patterns corresponding to 11 3-digit numbers displayed. For the typewriter, two keys were depressed sequentially for each 3-digit pattern; for the large chord keyboard, 1, 2, or 3 keys were depressed simultaneously for one 3-digit pattern, while for the small chord keyboard 1, 2, 3, or 4 keys were activated at the same time.
After practicing 20 hours, six subjects on each keyboard performed 800 experimental encodings. The typewriter group performed an average of 40 sorts per minute (this is actually 80 key presses per minute), while the large chord keyboard group and small chord keyboard groups averaged 49 and 55 sorts (or chords) per minute, respectively. No learning curves over the 20 hours of practice were provided. The training schedule, e.g. hours per day, number of days, etc., was not indicated.

2.4.7 Sidorsky (1974).

Sidorsky (1974) experimented with a one hand combined chord and sequential keyboard for use in battlefield data entry. The keyboard consisted of five keys, one for each digit of the right hand. Single characters were generated by two consecutive inputs of single keys or chords. Each input was either the thumb, little finger, or combinations (chords) of the index, middle, and ring fingers. For example, the letter F was produced by simultaneously pressing the keys under the index, middle, and ring fingers followed by depression of the index finger key. Ten subjects were taught about 40 characters (letters, numbers, and punctuation). Subjects were then given 20 text tests (each 255 characters long, consisting of typical sentences) each day to type. The training and testing process was conducted in 10 sessions of 1/2 hour over 10 to 15 days, a total of 5 hours. Considering only each subject's fastest trial, the average speed achieved was 63 CPM.

Sidorsky (1974) provided no information on performance progress from day to day. He only counted the fastest trial a subject obtained on any day. Considering the size of the character set, 40, and the length of practice, the
subjects attained fast data entry, because 63 CPM actually corresponded to twice as many chord activations.

2.4.8 Bequaert and Rochester (1977) and Rochester, Bequaert, and Sharp (1978).

A chord keyboard consisting of two rows of five keys was developed by Rochester et al. (1978) for use with one-hand. Figure 8 shows the layout of the keys and the patterns of keys required to generate characters; the bottom part of the figure shows the symbols activated by the shift function. Four subjects learned about 54 characters (letters, punctuation, and symbols, but no numbers).

Bequaert and Rochester (1977) and Rochester et al. (1978) appear to have reported on the same experiments. Subjects were trained for one 50-minute session a day, 5 days a week. After an average of 49 sessions or 37 hours, subjects could touch-type all 54 characters. Their average speed at this time was 18 WPM (90 CPM), however, this was achieved during repeated practice of one text file. The subjects then strived to increase their typing speed. They did this by repeatedly practicing a short text passage, alternated about half of the time with new typing material. The results are difficult to understand. For example, Rochester et al. (1978) stated that three subjects achieved typing speeds of over 40 WPM (200 CPM); the fourth gained a speed of 25 WPM (125 CPM) after a total of about 90 hours of practice. These speeds were reported as achieved on previously unpracticed material. Whereas, Bequaert and Rochester (1977) reported typing speeds of 46, 47, 32, and 45 WPM for previously unpracticed material. They also provided performance progress
Figure 8. View of Chord Keyboard Developed by Rochester et al. (1978). Taken from Rochester et al. (1978).
curves as a function of one-hour sessions. It appears that the maximum typing performance occurred at the final session. It is assumed the tests, given (once every four sessions) to judge typing speed, were new (unpracticed) material, but it was not explicitly stated.

It is difficult to determine any trends in performance progress from the learning curves. First, the tests were only given every four sessions. Second, it is not known if new or old material was used, how long the tests were, or what the distribution of characters in the test was. Therefore, it is hard to determine if a "maximum" performance was approached.

2.4.9 Gopher and Eilam (1979).

A one-hand chord keyboard similar to that used by Sidorsky (1974) was tested by Gopher and Eilam (1979). The keyboard consisted of only four keys, one for each digit of the right hand except the little finger. Two consecutive chords by combinations of the three fingers were required to create one (Hebrew) character. The thumb was pressed sequentially with one of the three-finger chords to activate an editing function.

In the first experiment by Gopher and Eilam (1979), subjects were taught 30 letters and functions. The training occurred over seven one-hour sessions. Three one-hour sessions separated by two hours were administered on day one, two one-hour sessions on day two, and two one-hour sessions six weeks later (to test retention). At the end of the seventh session subjects typed an average of 65 CPM (130 strokes). There was linear increase in speed over the seven sessions, even with six weeks off after five sessions.
In the second experiment, Gopher and Eilam (1979) taught subjects 40 letters and functions in six one-hour sessions spread over three to five weeks. For half of each session, subjects practiced text from a newspaper while the other half they practiced nonsensical material. Subjects reached an average speed of 56 CPM on text and 41 CPM on nonsense trials. Their performance progress on both sets of material was close to linear.

For the same amounts of practice, the subjects in experiment #1 consistently typed 10 CPM faster then subjects in experiment #2. One explanation of this phenomenon may be the larger character set in the second experiment. The increase in number of choices of chords may have caused reaction times to be longer and typing speed to be lower. This effect may mean that peak performance is attained faster with smaller character sets. It is difficult to interpret if maximal speed might be different or if time to reach top speed varies by character set size.

2.4.10 Gopher, Hilsenrath, and Raij (1985); Gopher (1986); and Gopher and Raij (1988).

In a set of related studies, Gopher et al. (1985), Gopher (1986), and Gopher and Raij (1988) performed experiments on a one-hand five-key chord keyboard, one key for each digit. A total of 31 chords were possible considering 1, 2, 3, 4, or 5 finger combinations. The most recent and comprehensive of these studies, reported by Gopher and Raij (1988), will be discussed in detail.

Three groups of subjects were assigned to one of three keyboards: the QWERTY type keyboard, a one-hand chord keyboard, and a two-hand chord keyboard (each hand could produce all characters). Gopher and Raij (1988)
taught all subjects 22 Hebrew letters and the space character. All subjects in the three groups were able to memorize the patterns for the characters in 30-45 minutes. The subjects then participated in 35 one-hour sessions; three to four sessions were held a week. Each session consisted of 15 three-minute typing trials: each trial was followed by a one-minute rest break. The average CPM for each session (mean of 15 trials) was then plotted versus session to obtain a learning curve (Figure 9). The characters per minute plotted on the chart is an average over all subjects.

At the end of the thirty-fifth session the performance of the one-hand chord keyboard group was 178 CPM; for the two-hand chord keyboard group performance was 208 CPM, while the QWERTY group had a speed of 118 CPM. The results of the one-hand chord keyboard are most applicable to this study. The rate of learning between sessions 20-24 was 4.36 letters per session for the one-hand chord keyboard; between sessions 26-35, the rate of learning had dropped to 1.86 letters per session. This indicates a flattening of the learning curve beyond 30 hours of training. While apparently peak performance had not been obtained, progress was clearly slowing for the one-hand chord keyboard group after 30 sessions.

2.4.11 Richardson, Telson, Koch, and Chrysler (1987).

Richardson et al. (1987) compared three types of keyboards for a mail encoding task: a one-hand conventional calculator layout, a two-hand 10-key sequential keyboard like the top row of a QWERTY layout, and a two-hand 10-key chord keyboard with 5 keys for each hand. Richardson et al. were interested in data entry of ZIP codes so the subjects were taught only the ten
Figure 9. Typing Speed for Three Keyboards as a Function of Practice. Taken from Gopher and Raji (1988).
numerals. On the chord keyboard, each of the hands could input all ten numbers. Subjects were presented single numbers and required to press the correct key or chord. They had to encode an average of 100 numbers per minute with 95% accuracy for three consecutive tests (300 numbers per test). Next, two digit strings were presented with a passing criterion of 70 strings per minute with 95% accuracy. Finally, training was completed with subjects entering three digit strings at a rate of 65 strings per minute with 95% accuracy.

Training was conducted in sessions that were three hours and ten minutes long. Within each session, subjects practiced for 30 minutes, followed by a 10 minute break, followed by 30 minutes of practice, and so on. The mean time for training of the calculator and sequential keyboards to the criterion of two digit strings (70 strings per minute or 140 CPM) was estimated at 22 hours; for the chord keyboard, it was 97 hours. Therefore, the time to reach 140 CPM for a character set size of 10 was 22 hours for the two sequential keyboards and 97 hours for the chord keyboard. However, the training methods used to teach the subjects were peculiar. First, the subjects were not given any feedback on their accuracy during a trial. It is also not known if the subjects knew the final criterion needed to advance to the next stage. Subjects may have had to randomly set their speed and accuracy levels until they hit the correct criterion. Second, although the chord keyboard group could enter the strings independently with each hand they were not given specific instructions such as enter the first number with the left hand and the second with the right hand.
2.5 Ternary Chord Keyboard Experiments.

As stated earlier, the ternary chord keyboard differs from all chord keyboards discussed so far in that its keys have three states instead of just two (Figure 1). Therefore, previous studies on the ternary chord keyboard (TCK) provided much of the foundation for this study.

2.5.1 Fathallah (1988) - TCK #1.

A study to compare performance on the TCK versus the QWERTY keyboard was conducted by Fathallah (1988). Figure 10 shows the Ternary Chord Keyboard Model #1. Four subjects were trained to use the TCK, and another four learned the QWERTY keyboard. Both groups of subjects were taught a total of 17 characters composed of 15 letters, space, and help. All subjects were taught the characters in the same manner. For the TCK group, chords were generated by using only two fingers, one finger from each hand. Practice sessions (and all other sessions) lasted about 1 1/2 hours broken into 15 minute sessions of typing followed by 5 minute breaks. Five characters were learned per session and then reviewed on the fourth and final practice session. Then, in what was called training sessions, the subjects were given text files to type which were made up of words which used only the 15 letters. The files were approximately 880 characters long. Subjects were trained until they met the following criteria: 97% accuracy per character, and a mean response time of 800 msec per character. The two keyboards were evaluated in terms of number of 15-minute sessions needed to meet the criteria: the average number of sessions were 10 for the QWERTY group and 12 for the TCK group (these were not significantly different).
Figure 10. Ternary Chord Keyboard Model #1 (dimensions in cm, not to scale).
After training was completed, subjects participated in what was called test sessions. Four 15-minute test sessions were given per day for five days. On the fifth day average speed was 545 msec/character (110 CPM) for the QWERTY group and 571 msec/character (105 CPM) for the TCK group; the difference was not significant. In summary, subjects attained an approximate typing speed of 107 CPM with a character set size of 16 after an average of 20 total hours of practice on either keyboard.

2.5.2 Kroemer (1990) - TCK #2.

Kroemer (1990) reported on the first training of subjects on TCK #2 (called #2 because it was modified from the one used by Fathallah) with a full character set. Figure 11 shows the TCK #2. A total of 64 characters consisting of 26 letters, 10 numbers, 4 cursor functions, and 24 punctuation marks, symbols, and editing features were taught. Twelve subjects were trained in two one-hour sessions per day. Characters were presented in "blocks" of six to ten. Subjects were taught one block of characters and tested. Then another block of characters was added until all 64 characters were learned. Subjects were considered to have learned the keyboard once they could pass a test including all the characters (presented four times each in random order) with 97% accuracy two times consecutively. On the average, subjects learned all characters in approximately four hours.

The next stage in the experiment was aimed at increasing the subjects' speed. They were first given 20 text files that were 406 characters long, each called a "trial". These were called "equal distribution trials" because each of 58 characters (the 4 cursor functions, shift, and backspace were not incorporated in
Figure 11. Ternary Chord Keyboard Model #2.
these trials) occurred 7 times, though randomly presented. By the twentieth trial, subjects were averaging 54 CPM. Next, 20 text trials, 390 to 411 characters long, were typed by the subjects; the text, consisted of meaningful sentences which attempted to capture the majority of the characters. At the end of the fortieth trial, average speed was 78 CPM. The performance progress over all 40 trials is shown in Figure 12.

In this experiment, subjects completed four trials in each one-hour session. Since some subjects were faster than others, not all needed a full hour to type the trials. Therefore, it is difficult to relate performance to hours of practice. However, the total time spent using the keyboard averaged approximately 12 hours.

2.5.3 Kroemer (1990) - TCK #3.

Kroemer (1990) reported on experiments with a modified keyboard, TCK #3, as shown in Figure 13. The training procedure for TCK #3 was essentially the same as TCK #2, except each subject was trained in one two-hour session per day. Ten subjects learned all 64 characters in an average of about three hours.

After training, subjects worked on improving speed, continuing the same schedule as in the learning phase, i.e. one session per day lasting two hours. The subject typed 40 text "trials" of meaningful sentences; each trial was 391 to 513 characters long. (No "equal distribution" trials were presented.) On the average, subjects began trial number one keying 36 CPM; by trial 40 they reached an average of 70 CPM. The performance progress for the 40 trials is shown in Figure 14. Total time spent on the keyboard can not be directly
Figure 12. Learning Curve for the Ternary Chord Keyboard #2.
Figure 14. Learning Curve for the Ternary Chord Keyboard #3.
expressed by the number of trials since time to type each trial was not constant. However, the total hours spent practicing on the keyboard was approximately 10 hours.

Two subjects continued practicing past the first 40 trials; each subject typed an additional 120 trials, for a total of 15 to 17 hours. Their highest inputs per trial were 134 and 183 CPM, respectively. Yet, until the end both subjects' performance still increased in a seemingly linear fashion.


A pilot study was conducted on a one-hand TCK by McMulkin and Kroemer (1991) and Lee and Kroemer (1991). The apparatus used for the experiment was the right-hand side of the keyboard used by Kroemer (1990), TCK#2 shown in Figure 11. A total of 24 two-finger chords can be produced on the one-hand TCK. The method in which chords were generated on the one-hand TCK is different from the method used with the two-hand TCK. For the two-hand TCK, chords were always produced by using one finger from each hand; on the one-hand TCK, chords were produced by using two fingers from the right hand.

Twelve subjects were taught 24 letters of the alphabet (V and Q not included). Chords were grouped into blocks of eight letters. In teaching a block of eight finger patterns, care was taken to make sure each chord was practiced an equal number of times, which is different from the training program used in the earlier experiments (Kroemer, 1990). The subjects learned all 24 chords in an average of one hour.
The subjects returned on four consecutive days for one-hour testing sessions. In each session, they completed five "trials". Each trial consisted of the 24 letters randomly presented 10 times for a total of 240 characters. The average typing speed began at 33 CPM and reached 63 CPM by the twentieth trial. The performance progress is shown in Figure 15. The main purpose was to collect response times for all 24 chords, so that the 18 "fastest" could be selected.

2.6 Length of Training Session.

As alluded to earlier, the schedule of training can have a profound effect on progress of speed acquisition. Glencross and Bluhm (1986) trained 242 persons on the QWERTY keyboard. Two hundred thirty-three people were trained using ten 45-minute sessions spread over two weeks, one lesson per weekday. Nine subjects received the same lessons, except that two sessions were given per day for five days. At the end of the training, the two-week group had an average keying speed of about 14 WPM as compared to the one-week group's speed of about 11.2 WPM, a significant difference (p=0.012).

Baddeley and Longman (1978) conducted the most comprehensive experiment on the effect of training session length on acquisition of typing speed. Four levels of training schedule were established: one one-hour session per day (1 X 1h); two one-hour sessions per day (2 X 1h); one two-hour session per day (1 X 2h); and two two-hour sessions per day (2 X 2h). Multiple sessions were separated by at least two hours of break. All groups were trained for at least 60 hours; this means the 1 X 1h group had a total training period of 12 weeks, the 1 X 2h and 2 X 1h groups trained for 6 weeks, and the 2 X 2h
group trained for 3 weeks. The training time until the groups became operational was listed as follows: 1 X 1h - 35 hours, 2 X 1h - 42.6 hours, 1 X 2h - 43.2 hours, and 2 X 2h - 50 hours. This means the latter groups were operating less efficiently per hour, but completed training much faster in practical terms of weeks.

After becoming operational, the remaining portion of the 60 hours was spent increasing speed. Typing tests were given once an hour. At the end of 60 hours each of the groups obtained the following speeds: 1 X 1h - 79 CPM, 2 X 1h - 73 CPM, 1 X 2h - 71 CPM, and 2 X 2h - 65 CPM. The speed of the 1 X 1h group was significantly faster than the 1 X 2h and 2 X 2h groups. The 2 X 1h group was significantly faster than the 2 X 2h group. The performance progress by hour is shown in Figure 16. An important finding was that at every hour of practice, the rank order of groups from fastest to slowest was 1 X 1h, 2 X 1h, 1 X 2h, then 2 X 2h.

Baddeley and Longman's (1978) results indicated where the optimum efficiency for training period length lies. Although less efficient, longer sessions decreased the total number of weeks needed to perform an experiment. To further illustrate this point, the 2 X 1h and 1 X 2h groups reached 80 CPM (the 60 hour level of the 1 X 1h group) in approximately 75 hours or 7.5 weeks. At that time, the 1 X 1 group had barely become operational.

2.7 Format of Text for Testing.

The format of the text used to test keying performance can affect the measures of speed. The main variable in text is whether it is nonsensical, such as in a random presentation of letters, or whether it makes sense such as by
Figure 16. Effect of Training Schedule on Typing Performance. Taken from Baddeley and Longman (1978).
having random words, phrases, or sentences. Gopher and Eilam (1979), Sidorsky (1974), Alden, Daniels, and Kanarick (1972), and Seibel (1972) all indicated that faster performance will be obtained if the text material makes some sense. However, in this study, data were entered in the form of numbers and mathematical operators; there seems to be little redundancy or predictable order in numerical data entry (Seibel, 1972). Because of the lack of redundancy in numerical data, this present study probably did not find keying speeds comparable to a study which might have used sentences.

2.8 Sequences of Finger Movements that Yield Fast Typing Rates.

The time between keystrokes on the QWERTY keyboard has been measured by several investigators (Salthouse, 1986; Salthouse, 1984; Gentner, 1983; Evey, 1980; and Kinkead, 1975). There has been general agreement that the categories of consecutive keystrokes that rank from fastest to slowest are as follows: 1) successive strokes from different hands, e.g. "th", 2) successive strokes from different fingers of the same hand, e.g. "er", 3) same key struck twice by the same finger, e.g. "ss", and 4) different keys struck by the same finger, e.g. "ed". Theses rules hold for skilled typists, not beginners.

Again, these rules do not seem to be helpful for numerical entry. Since numerical entry has no order or redundancy, it is difficult to develop design guidelines for assigning the numbers to particular chords based on the four rules above. In addition, since the experiment conducted was constrained to one-hand use of a keyboard, the fastest variety of successive keystrokes (between hands) could not be implemented.
2.9 Which Hand to Use on a One-Hand Keyboard.

There is some disagreement on the issue of which hand should be used in a one-hand keyboard task. Morgan, Drake, Heck, and Long (1981) trained two groups of people on a 10-key calculator, a left-handed group and a right-handed group. They found the left hand group to be significantly faster. However, Dvorak (1943) and Dvorak, Merrick, Dealey, and Ford (1936) argue that the right hand should be used more frequently in keyboard tasks. Since there is no clear evidence of an advantage for either hand, the right hand was assumed to be appropriate for the completed experiment. Also, using two fingers of the same hand to generate a chord requires greater dexterity than a strict tapping task. The preferred hand probably possesses greater dexterity.

2.10 Literature Summary.

The ability of people to learn keyboard operation depends (among other variables) on the number of characters taught, type of keyboard used (sequential or chord), and criterion employed to establish proficiency. Total amount of training time, number of trials or sessions, and total inputs have been used to predict and analyze performance progress. It does not appear that any of these criteria have been investigated to determine the most effective one. Table 1 provides a summary of the findings, as they pertain to the objectives of the present study.

The first experimental objective is to investigate the performance progress of subjects on a keyboard. Few studies have evaluated keyboard performance from initial learning to peak performance; thus, performance progress on keyboards is not well known. The training time to maximal
Table 1. Summary of Important Variables in Keyboarding Studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Type of Keyboard</th>
<th>Character Set Size</th>
<th>Training Schedule</th>
<th>Total Hours</th>
<th>Total Characters</th>
<th>CPM at end</th>
<th>Provide Learning Curve?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapman (1919)</td>
<td>QWERTY</td>
<td>65</td>
<td>n/a</td>
<td>180</td>
<td>n/a</td>
<td>240</td>
<td>yes</td>
</tr>
<tr>
<td>Thurstone (1919)</td>
<td>QWERTY</td>
<td>65</td>
<td>2 hrs/day 5 days/wk</td>
<td>280</td>
<td>250 pages</td>
<td>205</td>
<td>yes</td>
</tr>
<tr>
<td>Green (1940)</td>
<td>QWERTY</td>
<td>65</td>
<td>1 hr/day 5 days/wk</td>
<td>360</td>
<td>n/a</td>
<td>235</td>
<td>yes</td>
</tr>
<tr>
<td>Klemmer (1958)</td>
<td>Chord</td>
<td>30</td>
<td>1 hr/day 3 days/wk</td>
<td>35</td>
<td>15,000 words</td>
<td>225</td>
<td>yes</td>
</tr>
<tr>
<td>Lockheed &amp; Klemmer (1959)</td>
<td>Chord</td>
<td>136</td>
<td>1 hr/day 50 days</td>
<td>45</td>
<td>n/a</td>
<td>40</td>
<td>no</td>
</tr>
<tr>
<td>Cornog et al. (1963)</td>
<td>Chord</td>
<td>36</td>
<td>1.5 hr/day 11 weeks</td>
<td>190</td>
<td>n/a</td>
<td>232</td>
<td>no</td>
</tr>
<tr>
<td>Conrad &amp; Longman (1965)</td>
<td>QWERTY, Chord</td>
<td>36</td>
<td>3.5 hrs/day 5 days/wk</td>
<td>120</td>
<td>n/a</td>
<td>92</td>
<td>yes</td>
</tr>
<tr>
<td>Bowen &amp; Guinness (1965)</td>
<td>Chord</td>
<td>11</td>
<td>n/a</td>
<td>20</td>
<td>n/a</td>
<td>80</td>
<td>no</td>
</tr>
<tr>
<td>Sidorsky (1974)</td>
<td>Chord</td>
<td>40</td>
<td>0.5 hr/day 10 days</td>
<td>5</td>
<td>n/a</td>
<td>63</td>
<td>no</td>
</tr>
<tr>
<td>Rochester et al. (1978)</td>
<td>Chord</td>
<td>54</td>
<td>50 min/day 5 days/wk</td>
<td>90</td>
<td>n/a</td>
<td>200</td>
<td>yes</td>
</tr>
<tr>
<td>Gopher &amp; Eilam (1979)</td>
<td>Chord</td>
<td>30</td>
<td>7, 1 hr sess</td>
<td>7</td>
<td>n/a</td>
<td>65</td>
<td>yes</td>
</tr>
<tr>
<td>Gopher et al. 85, 86, and 88 (1987)</td>
<td>Chord</td>
<td>23</td>
<td>1 hr/day</td>
<td>35</td>
<td>n/a</td>
<td>208 (2-hand)</td>
<td>yes</td>
</tr>
<tr>
<td>Richardson et al. (1987)</td>
<td>Chord</td>
<td>10</td>
<td>3 hr/day 30 days</td>
<td>97</td>
<td>n/a</td>
<td>140</td>
<td>no</td>
</tr>
<tr>
<td>Fatullah (1988)</td>
<td>Chord</td>
<td>17</td>
<td>1.5 hrs/day 12 days</td>
<td>20</td>
<td>n/a</td>
<td>105</td>
<td>yes</td>
</tr>
<tr>
<td>TCK #2 (1990)</td>
<td>Chord</td>
<td>64</td>
<td>2, 1 hr sess</td>
<td>12</td>
<td>16,000</td>
<td>78</td>
<td>yes</td>
</tr>
<tr>
<td>TCK #3 (1990)</td>
<td>Chord</td>
<td>64</td>
<td>2 hrs/day</td>
<td>10</td>
<td>18,000</td>
<td>70</td>
<td>yes</td>
</tr>
<tr>
<td>One-Hand TCK (1991)</td>
<td>Chord</td>
<td>24</td>
<td>45 min/day 5 days</td>
<td>3</td>
<td>2,400</td>
<td>63</td>
<td></td>
</tr>
</tbody>
</table>
performance seems to be largely dependent on character set size, see Table 1. Since only 18 chords are used for this study, the training time is expected to be considerably shorter than for a set size of 64. The training schedule has a large effect on the learning curve; this study uses a schedule that is as efficient as possible to obtain results rapidly.

The second experimental objective is to find a function which predicts learning and evaluate three different criteria to assess which criterion is most effective at predicting performance progress. Only three of the reviewed studies attempted to find a function which predicted learning, Thurstone (1919), Kroemer (1990), and McMulkin and Kroemer (1991). The conclusions that can be drawn about each criterion from the literature may be summarized as follows:

1) Number of hours of practice

Fourteen of the seventeen studies summarized in Table 1 used practice time to describe performance progress. In none of these studies was it investigated whether this was the best predictor. The assumption that hours of practice was indeed the best criterion should be tested against other predictors, which is one goal of this study.

The amount of practice to reach maximal performance with an 18-chord set was estimated from the studies at 50 hours. This was based on the assumption that the subjects would reach a peak speed of close to 200 CPM (this is an interpolation of the results listed in Table 1). With character set sizes of 50 or more, 200 CPM was reached after about 200 hours (Chapman, 1919; Thurstone, 1919; and Green, 1940). Therefore, with a character set size of only
18 the time was expected to be about a fourth as long. However, due to the
differences in training schedules and method of testing, this remains a guess.

2) Number of trials or characters

Only five of the studies reviewed in Table 1 recorded the number of
characters practiced as a function of performance. In none of these studies
were subjects able to attain peak performance, so an estimate of characters
practiced until peak performance was almost impossible. There was no
discussion that number-of-characters-typed was the best predictor in any of the
five studies. Only Thurstone (1919) provided learning curves for both hours of
practice and pages typed. However, he did no analysis to show which criterion
provided a better prediction.

3) Subjects' Opinion

None of the studies considered the opinion of the subject as a method to
assess how close or far the subject was from maximal performance.
3. METHOD

3.1 Subjects.

Five subjects participated in this experiment. The only criteria used to select subjects was that they write with their right hand and have no history of wrist problems (such as carpal tunnel syndrome). Four of the subjects were female, and one was male. The subjects' ages ranged from 20 to 29 years. The total time commitment of each subject was 60 hours. Subjects were compensated at a rate of $5.00 per hour, plus a $50 bonus for participating for all 60 hours, for a total of $350. None of the subjects dropped out of the experiment.

3.2 Apparatus.

The one-hand Ternary Chord Keyboard, shown previously in Figure 11, was used for this study. Activation of a key was detected by microswitches. The microswitches were connected to an Input/Output carrier on an IBM (AT) computer via a bus cable. A software program (written by VATELL Corporation) interpreted and manipulated inputs from the TCK.

For each trial the following data were recorded: subject number, trial number, total time to complete the trial, and the number of errors committed by the subject. Also, the following data were collected on every chord within each trial: subject number, trial number, chord number, and response time for the chord. If the chord was not keyed correctly, the incorrectly entered (actual) chord was recorded.
3.2.1 Dimensions of the One-Hand TCK.

The physical dimensions and positions of the keys for the one-hand TCK are shown in Figure 17. A palm rest was provided for the subjects to use if they wished. The wooden palm rest was shaped approximately like a half cone, 11.5 cm long, sloped from a radius of 2.7 cm at the thumb side of the palm to a radius of 1.6 cm at the little finger side of the palm. The palm rest was adjustable longitudinally (4.5 to 11 cm from the center of the keys to the center of the palm rest) and laterally (1 cm in either direction from the center). It was fastened to the base of the keyboard by velcro strips. The entire keyboard base could be rotated in roll, pitch or yaw. The keyboard (rotated as preferred by the subject, no specific pattern) and chair height were adjusted so that the subject felt comfortable, the wrist was straight, and the elbow formed about a 90 degree angle.

3.2.2 Chord Coding.

The method to assign the numbers and functions to the chords was determined largely from the experiments conducted by McMulkin and Kroemer (1991) and Lee and Kroemer (1991). Of the 24 possible chords, 6 were eliminated, based on user preference and response times. The remaining 18 chords were assigned by VATELL Corporation to the numbers and functions. On an adding machine, it was assumed the ten numbers, "decimal point", and "plus", "minus", "multiply", "divide", "subtotal", and "total" functions are all used with about equal frequency. No literature could be found which ranked the frequency of these 18 numbers and functions. Therefore, some of the assignments were chosen based on ease of learning. All the "odd" numbers
Figure 17. Dimensions of the One-Hand Ternary Chord Keyboard (in cm).
were assigned to chords in which both the fingers moved backward. All the “even” numbers were assigned to chords in which the fingers moved forward. The “backspace” chord was assigned to the chord in which the index finger moves backward and middle finger forward; this is like turning a wheel where the top of the wheel moves to the left. No learning principle existed for the remaining seven functions, so they were matched with the remaining seven chords. Because each of the chords was to appear equally often in the text trials, the chord assignments should not have had an effect on performance. Figure 18 shows how the chords were assigned to the characters. The letter S was used to represent "Subtotal", the letter T represented "Total", and an arrow, \[\Leftarrow\], represented "Backspace".

3.3 Procedures.

3.3.1 Experimental Design.

One of the objectives of the experiment was to determine a function which effectively predicts learning and evaluate a set of criteria for predicting performance progress and peak keying speed. Therefore, the regressor variables used to predict performance were number of hours spent practicing, and number of repetitions (trials). The dependent measures recorded were time to complete a trial/test, number of errors during a trial, and opinion of the subjects about their performance at the end of each week. From the first two dependent measures, characters per minute were computed for each trial and for each time increment of practice.
(The chord numbers describe which fingers were used to generate a chord. The first number of the chord represents the first finger's direction while the second number represents the second finger and its movement direction. For example, the chord number 36 represents the middle finger moving backward and the ring finger moving forward.)

<table>
<thead>
<tr>
<th>Character</th>
<th>Chord</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>6</td>
<td>46</td>
</tr>
<tr>
<td>7</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>48</td>
</tr>
<tr>
<td>9</td>
<td>57</td>
</tr>
<tr>
<td>0</td>
<td>68</td>
</tr>
<tr>
<td>+</td>
<td>24</td>
</tr>
<tr>
<td>-</td>
<td>23</td>
</tr>
<tr>
<td>*</td>
<td>45</td>
</tr>
<tr>
<td>/</td>
<td>36</td>
</tr>
<tr>
<td>. (Decimal Point)</td>
<td>13</td>
</tr>
<tr>
<td>S (Subtotal)</td>
<td>25</td>
</tr>
<tr>
<td>T (Total)</td>
<td>16</td>
</tr>
<tr>
<td>← (Backspace)</td>
<td>14</td>
</tr>
</tbody>
</table>

Figure 18. Chord Assignments for the Numeric One-Hand Ternary Chord Keyboard.
3.3.2 Schedule of Practice.

Subjects were scheduled for one one-and-a-half hour session per day, five days a week. Subjects participated for eight weeks for a total of 60 hours. (As pointed out in the literature review this may not have led to optimum efficiency for each hour of practice, but the study was to be completed in approximately eight weeks.) Only one keyboard was available for experimentation; this meant one-and-a-half hour sessions required a chunk of 7.5 hours per day be allotted to testing (this was close to the upper limit of the time available by the experimenter). Subjects were scheduled for the same times each day. Having the sessions the same time each day was the most convenient for the subjects and greatly reduced the probability of them dropping out. Daily sessions also allowed the subjects to participate in the experiment before, after, or between classes, and avoided conflicts with other activities. Overall, 1.5-hour sessions offered the best compromise between utility of each hour of practice and convenience for the subjects.

Due to a variety of reasons, each subject missed some of the sessions. Any session that was missed was rescheduled for another day either at the end of the eight weeks or on a weekend. Subjects never participated in two sessions in one day.

3.3.2.1 Breakdown of Sessions.

The first session was dedicated to teaching the subjects the 18 characters (training program described in detail in the next section). The second through the fortieth sessions had the same format. The subjects were given text consisting of 504 characters to input. Typing each such text was
called a "trial" (the terms text and trial are used interchangeable from this point on). During each session the subject was presented a trial to type. The subject was instructed to input the text as rapidly as possible maintaining 97% accuracy. The subjects took approximately 15 minutes to type the first trial. After the end of the trial, subjects were given a break of two to three minutes and then started another trial. As the subjects typed the trials faster, they were given shorter breaks, of about one minute to maintain a fairly constant ratio between practice and rest. The experimenter determined how long the rest breaks would be so that the ratio of practice to rest was approximately constant (about two to three minutes practice to every one minute of rest). The session continued in this way until the end, after one-and-a-half hours.

3.3 2.2 Training Program.

During the first session the subjects were taught the 18 chords. The characters were taught in two "blocks": first, the numbers 1 to 9, and 0; second, the functions "plus", "minus", "multiply", "divide", "decimal point", "backspace", "subtotal", and "total". Within each block, the first character was presented along with the finger pattern corresponding to that character. The subject then practiced the character five times. The second through fifth characters were presented in the same manner. A "mini-quiz" was then given over the first five characters in the number block, each character presented in random order four times. During the "mini-quiz", no finger patterns were displayed for the characters unless the subject entered a chord incorrectly. The sixth through tenth characters were then presented five times each. A "mini-quiz" was then given over the final five characters in the number block. After the first learning
block, a quiz was given over all the characters in that block; each was presented in random order a total of three times. The subject had to pass the quiz two consecutive times with 97% accuracy; there was no time limit. An accuracy of 97% was selected so that subjects could not incorrectly enter one chord all three times it was presented and still pass. If the subject did not pass the quizzes, the learning block was repeated and the quizzes repeated at the end of that learning block.

After passing the quizzes, the next block of characters was presented in the same manner. Quizzes were given over the second block to ensure the subject had learned the eight symbols. Upon completion of the second learning block quizzes, a cumulative quiz over all characters was given. Each character was presented randomly three times. The subject had to pass the quiz two consecutive times with 97% accuracy (again subjects could not miss 1 of the 18 chords all three times and still pass). If the quiz was failed, the subject had the option of reviewing a block or retaking the final quiz. After passing two cumulative quizzes, the subject was considered to have learned the 18 characters.

The number of keystrokes performed during training as well as the time to complete the training session was recorded for all subjects.

It might be argued that this training program had not been experimentally verified as being the most effective method of teaching the chords. This is true, but the same training program has been used successfully in the experiments conducted by Kroemer (1990), and McMulkin and Kroemer (1991). There a total of 64 chords were taught in three to four hours, and 24 chords were taught
in an hour. These results indicated that the training program brought about a short training time.

3.3.2.3 Makeup of Trials.

Each trial contained 504 characters; therefore, each of the characters was presented 28 times. The trials were generated using a PASCAL program which randomly selected the order of the characters. Each trial presented to the subjects was a different trial created by the program. However, all the subjects were presented with the same trials in the same order. As subjects' keying speed became faster it took the subjects less time to complete the trials. Due to the variable keying speed of the subjects, some typed trials that were never presented to others. Appendix A shows an example of a trial.

3.3.3 Determining Peak Performance.

A problem in analyzing the experimental results is to establish a subject's peak performance, i.e. the fastest keying speed possible. Bittner (personal communication, April 11, 1991) suggested having the subjects perform a series of characters over and over; he assumed that this allows them to develop a fast motor skill pattern, thus give a measure of peak performance.

Following Bittner's suggestions, at the end of the final session, subjects continuously typed a single series of characters. Five different character strings were used: 6.7-3S, 4/0<2T, 58+1-9, 1+2-3., and 123456. Each trial was 504 characters long, consisting of 84 repetitions of one of these five character strings.
3.3.4 **Subjects' Opinion.**

Every subject knew that an objective of the study was to reach maximal input speed. It was hypothesized that the subjects' opinion of when they were typing as fast as they could may be a good measure of when peak performance was obtained. Once a week the subjects were asked to rate their performance on a 0 to 9 scale, 9 representing the anchor for peak performance; Figure 19 shows the scale that was used.

3.4 **Experimental Protocol.**

The experiment was conducted in 40 one-and-a-half hour sessions, 5 days a week, for 8 weeks. In the first session, the subject was given the written experimental instructions to read (Appendix B). The experimenter then reviewed the instructions and answered any questions. The subject was given the informed consent form to sign (Appendix C). The subject was then seated in front of the keyboard; the seat height, the keyboard, and palm rest were adjusted until the subject was comfortable. The subject was not required to use the palm rest. Two subjects used the palm rest throughout the entire experiment. Two subjects never used the palm rest, and one subject started using it about halfway through the experiment. The subject was presented introductory information on the one-hand TCK and started with the training program. After learning the 18 chords, the subject was dismissed for the day.

At the start of the second session the subject was again required to take a cumulative quiz over all 18 characters until it was passed. The subject was then presented with the first trial to type. Additional trials were presented until the end of the session. As the session approached the end of one-and-a-half
Figure 19. Scale Used by Subjects to Rate Their Performance Each Week.
hours, the experimenter decided if enough time remained for an additional trial. The third through fifth sessions paralleled the second; the subject was required to pass a quiz and then practiced keying text trials. After the fifth session (after about 7.5 hours of practice), the subject was no longer required to take the cumulative quiz. During the sixth through the fortieth sessions, the subjects practiced keying text. At the end of the fortieth session, the subject was paid, thanked, and dismissed.

For all trials, the subject was instructed to increase input speed while maintaining at least a 97% accuracy level; 97% was selected to match the accuracy stressed in the training program. To help control the speed versus accuracy tradeoff, feedback was given to the subjects at the end of every trial. As stated before, for each trial the following data were recorded: subject number, trial number, total time to complete the trial, and the number of errors committed by the subject. Immediately after the completion of each trial, the characters per minute and accuracy were calculated from these data and displayed on the screen along with total time to complete each trial and number of errors. The subjects received immediate feedback on their speed and accuracy. They could then make adjustments in their performance to increase input speed, but maintain their accuracy levels. No specific rewards were given to the subjects to maintain 97% accuracy or increase their speed; presenting feedback of their performance to them was considered an effective way to control the variability due to speed versus accuracy.
4. RESULTS

4.1 Learning Results.

All five subjects passed the final training test within the first one-and-a-half hour session; the average learning time was 35 minutes (including quizzes) with a standard deviation of 8.3 minutes to achieve the required minimum of 97% accuracy on all 18 chords. The number of times a subject had to go through each training block ranged from two to four times and the number of quizzes per block taken to pass ranged from two to six.

4.2 Speed - Accuracy Performance.

The subjects were instructed to increase speed while maintaining a 97% accuracy level. Table 2 shows, for each subject, the average accuracy and standard deviation of the trials typed over the entire experiment. All the subjects had an average accuracy greater than 97%.

4.3 Using Number of Trials to Predict Performance.

The five subjects each completed different numbers of trials over the 60-hour experimental period, see Table 3. Analyses were done using individual subjects' data, except for chord and average performance analyses. This means that regressions for individual subjects include different numbers of data points, e.g. 487 points for subject 1 and 636 points for subject 3.

One of the objectives of this experiment was to find an equation that accurately describes the performance progress of each subject. The dependent variable being predicted is characters per minute. The keying speed of the
Table 2. Average Accuracy Across Trials for Each Subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Average Accuracy (in %)</th>
<th>Standard Deviation (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>97.39</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>98.51</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td>98.20</td>
<td>0.80</td>
</tr>
<tr>
<td>4</td>
<td>97.75</td>
<td>0.85</td>
</tr>
<tr>
<td>5</td>
<td>97.19</td>
<td>0.94</td>
</tr>
</tbody>
</table>
Table 3. Number of Trials Completed by Each Subject

<table>
<thead>
<tr>
<th>Subject</th>
<th>Number of Trials Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>487</td>
</tr>
<tr>
<td>Subject 2</td>
<td>622</td>
</tr>
<tr>
<td>Subject 3</td>
<td>636</td>
</tr>
<tr>
<td>Subject 4</td>
<td>509</td>
</tr>
<tr>
<td>Subject 5</td>
<td>516</td>
</tr>
</tbody>
</table>
subjects in characters per minute was calculated by dividing the correct entries (total number of characters minus number of errors) typed during a trial by the total time needed to complete the trial.

The major criterion used to determine which equations should be used was that they predict performance in a monotonically increasing fashion. Equations which would predict increasing and then decreasing performance were not considered, such as polynomial equations (e.g. \( B_0 + B_1 \cdot X + B_2 \cdot X^2 \)).

Five candidate functions were considered to fit the data. First, a simple linear relationship between characters per minute (CPM) and trials was used:

\[
CPM_i = B_0 + B_1 \cdot T_i \quad \text{(Equation 1)}
\]

where \( CPM_i \) is the characters per minute typed on the \( i \)-th trial (dependent variable), \( T_i \) is the \( i \)-th trial, and \( B_0 \) and \( B_1 \) are fitted coefficients.

Second, a relationship suggested by Bittner (1991) was used:

\[
CPM_i = B_0 + B_1 / T_i + B_2 / T_i^2 \quad \text{(Equation 2)}
\]

The first two equations were combined to generate the third function:

\[
CPM_i = B_0 + B_1 \cdot T_i + B_2 / T_i + B_3 / T_i^2 \quad \text{(Equation 3)}
\]

Fourth, a logarithmic function was tried of the form:

\[
CPM_i = B_0 + B_1 \cdot \ln(T_i) \quad \text{(Equation 4)}
\]

The final attempt to fit the data was by a Log-Log function:

\[
\ln(CPM_i) = B_0 + B_1 \cdot \ln(T_i), \text{ this reduces to}
\]

\[
CPM_i = C \cdot T_i^{B_1} \quad \text{(Equation 5)}
\]
where \( C = e^{B_0} \); see Appendix D for the derivation.

The subjects' performance was analyzed individually, not collectively. Each of the five functions above was fit to each of the subject's actual data. The statistical package SYSTAT was used to calculate the coefficients using the method of least squares. The criterion used to judge goodness of fit of the functions is the coefficient of determination, \( R^2 \), also calculated by SYSTAT. Table 4 summarizes the \( R^2 \) values obtained for each formula for each subject.

The regressions of the data of subject 2 are selected as a typical example of each of the five function's predictions plotted with the actual performance in Figures 20 to 23 and 25. Comparing the Figures 20 to 23 and 25, it becomes apparent that the Log-Log function most accurately follows the actual performance progress. This impression is supported by the statistical findings that the Log-Log function accounts for the largest portion of variation, i.e. has the highest \( R^2 \).

The plot of actual performance and predicted performance from the Log-Log equation (in Characters Per Minute typed) for each subject is shown in Figures 24 to 23. The Log-Log equation which best fit actual performance of each subject is listed in Table 5. Figure 29 shows the predictions for all individual subjects.

The Log-Log equation which was used to fit the actual performance had the form: \( \ln(\text{CPM}_i) = B_0 + B_1 \cdot \ln(T_i) \). The coefficients \( B_0 \) and \( B_1 \) which have a different value for each subject are listed in Table 6. A t-test can be used to indicate if any of the \( B_0 \) or \( B_1 \) coefficients for each subject are statistically different from one another (Neter and Wasserman, 1974). All \( B_0 \) coefficients
Table 4. Summary of R-Squared Values for All Functions Considered When Trial is the Regressor Variable.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
<th>Subject 5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CPM_i = Bo + B1 \cdot Ti$</td>
<td>0.899</td>
<td>0.825</td>
<td>0.817</td>
<td>0.819</td>
<td>0.802</td>
<td>0.832</td>
</tr>
<tr>
<td>$CPM_i = Bo + B1 \cdot (1/Ti) + B2 \cdot (1/Ti^2)$</td>
<td>0.361</td>
<td>0.430</td>
<td>0.427</td>
<td>0.498</td>
<td>0.440</td>
<td>0.431</td>
</tr>
<tr>
<td>$CPM_i = Bo + B1 \cdot Ti + B2 \cdot (1/Ti) + B3 \cdot (1/Ti^2)$</td>
<td>0.927</td>
<td>0.903</td>
<td>0.897</td>
<td>0.920</td>
<td>0.879</td>
<td>0.905</td>
</tr>
<tr>
<td>$CPM_i = Bo + B1 \cdot \text{Ln}(Ti)$</td>
<td>0.896</td>
<td>0.921</td>
<td>0.924</td>
<td>0.953</td>
<td>0.898</td>
<td>0.918</td>
</tr>
<tr>
<td>$CPM_i = C \cdot (Ti^2 \cdot B1)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[log-log]</td>
<td>0.961</td>
<td>0.953</td>
<td>0.955</td>
<td>0.973</td>
<td>0.939</td>
<td>0.956</td>
</tr>
</tbody>
</table>

$CPM_i = \text{Characters per Minute on the } i\text{-th trial}$

$Bo, B1, B2, \text{and } B3 \text{ are fitted coefficients}$

$Ti = \text{Trial}$

$C = \text{Exp}(B)$
Figure 20. Subject 2, Prediction of CPMi = Bo + B1*Trial and Actual Performance.
Figure 21. Subject 2, Prediction of \( CPM_i = B_0 + B_1/\text{Trial} + B_2/\text{Trial}^2 \) and Actual Performance.
Figure 22. Subject 2, Prediction of CPMi = B0 + B1*Trial + B2/Trial + B3/Trial^2 and Actual Performance.
CPM = 0.196 + 26.16*Ln(Trial)

Figure 23. Subject 2, Prediction of CPMi = Bo + B1*Ln(Trial) and Actual Performance.
CPM = 18.541*(Trial^{0.354})

Figure 24. Log-Log Prediction and Actual Performance, Subject 1.
CPM = 41.721^*(Trial^{0.222})

Figure 25. Log-Log Prediction and Actual Performance, Subject 2.
CPM = 48.231*(Trial^{0.199})

Figure 26. Log-Log Prediction and Actual Performance, Subject 3.
CPM = 32.137*(Trial^0.242)

Figure 27. Log-Log Prediction and Actual Performance, Subject 4.
Table 5. The Fitted Log-Log Equation for Each Subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Log-Log Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\text{CPM}_i = 18.541 \times T^0.354$</td>
<td>0.961</td>
</tr>
<tr>
<td>2</td>
<td>$\text{CPM}_i = 41.721 \times T^0.222$</td>
<td>0.953</td>
</tr>
<tr>
<td>3</td>
<td>$\text{CPM}_i = 48.231 \times T^0.199$</td>
<td>0.955</td>
</tr>
<tr>
<td>4</td>
<td>$\text{CPM}_i = 32.137 \times T^0.242$</td>
<td>0.973</td>
</tr>
<tr>
<td>5</td>
<td>$\text{CPM}_i = 36.379 \times T^0.217$</td>
<td>0.939</td>
</tr>
</tbody>
</table>

where $\text{CPM}_i$ is the characters per minute typed on the $i$-th trial (dependent variable) and $T$ is the $i$-th trial of practice.
Figure 29. Log-Log Prediction for Each Subject.
Table 6. Statistical Comparison of Coefficients Bo and B1.

Comparison Between Bo Coefficients

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bo Value</td>
<td>2.9197</td>
<td>3.7310</td>
<td>3.8761</td>
<td>3.4698</td>
</tr>
<tr>
<td>1</td>
<td>2.9197</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.8113 *</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.9564 *</td>
<td>0.1451 *</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.5501 *</td>
<td>0.2612 *</td>
<td>0.4063 *</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.6745 *</td>
<td>0.1368 *</td>
<td>0.2819 *</td>
</tr>
</tbody>
</table>

Comparison Between B1 Coefficients

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 Value</td>
<td>0.3545</td>
<td>0.2218</td>
<td>0.1995</td>
<td>0.2422</td>
</tr>
<tr>
<td>1</td>
<td>0.3545</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.1327 *</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.1550 *</td>
<td>0.0223 *</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.1123 *</td>
<td>0.0204 *</td>
<td>0.0427 *</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.1378 *</td>
<td>0.0051</td>
<td>0.0172 *</td>
</tr>
</tbody>
</table>

* indicates a significant difference, at p < 0.001
were found to be significantly different from each other (p < 0.001), see Table 6.
The B₁ coefficients for subjects 2 and 5 were not found to be significantly
different each other (p = 0.10), but all other comparisons between B₁
coefficients were found to be significantly different (p < 0.001), see Table 6.

4.4 Using Time to Predict Performance.

Another method of regressing performance is to predict the dependent
variable, characters per minute, from practice time. For example, performance
could be predicted from the equation \( CPM_i = B_0 + B_1 \cdot \log(P_i) \) where \( P_i \)
represents the i-th time increment of practice, for example 30 minute increments
\( (P_i = 1, 2, 3, \ldots ; \) not 30, 60, 90, \ldots \). During a given time increment of practice,
each subject typed a different number of trials.

All the data were collected in terms of time needed to complete a trial. To
create 30-minute time periods, the times to complete trials were added until the
total reached at least 30 minutes. Therefore, none of the periods were exactly
30 minutes, but none were less than 30 minutes. The time periods also
overlapped the sessions of practice. Session one might include the first 30-
minute period and half of the second 30-minute period; session two might cover
the other half of the second period, all of the third, and then part of the fourth.
The overlap of the periods is not constant across subjects either. The
procedure to create periods was repeated for 40, 50, and 60-minute time
periods. The average length of the 30, 40, 50, and 60-minute time increments
for each subject is shown in Table 7, along with the standard deviation. The
characters per minute typed for a period was calculated by averaging the
characters per minute of the trials that constituted a given time period.
Table 7. Average Length (and Standard Deviation) of 30, 40, 50, and 60 Minute Time Increments Used in the Regressions.

### 30 Minute Period

<table>
<thead>
<tr>
<th>Subject</th>
<th>Average (in Min)</th>
<th>Std Dev (in Min)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.7</td>
<td>2.01</td>
<td>67</td>
</tr>
<tr>
<td>2</td>
<td>32.2</td>
<td>1.43</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>31.9</td>
<td>1.22</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>32.4</td>
<td>1.99</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>32.2</td>
<td>1.52</td>
<td>71</td>
</tr>
</tbody>
</table>

### 40 Minute Period

<table>
<thead>
<tr>
<th>Subject</th>
<th>Average (in Min)</th>
<th>Std Dev (in Min)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42.5</td>
<td>2.11</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>42.0</td>
<td>1.47</td>
<td>54</td>
</tr>
<tr>
<td>3</td>
<td>41.4</td>
<td>0.93</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>42.5</td>
<td>1.54</td>
<td>53</td>
</tr>
<tr>
<td>5</td>
<td>42.3</td>
<td>1.48</td>
<td>54</td>
</tr>
</tbody>
</table>

### 50 Minute Period

<table>
<thead>
<tr>
<th>Subject</th>
<th>Average (in Min)</th>
<th>Std Dev (in Min)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.6</td>
<td>2.44</td>
<td>41</td>
</tr>
<tr>
<td>2</td>
<td>51.9</td>
<td>1.20</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>51.6</td>
<td>1.11</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>52.4</td>
<td>1.61</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>52.3</td>
<td>1.33</td>
<td>43</td>
</tr>
</tbody>
</table>

### 60 Minute Period

<table>
<thead>
<tr>
<th>Subject</th>
<th>Average (in Min)</th>
<th>Std Dev (in Min)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62.8</td>
<td>2.13</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>62.1</td>
<td>1.24</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>62.0</td>
<td>1.01</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>62.5</td>
<td>1.79</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>62.2</td>
<td>1.55</td>
<td>36</td>
</tr>
</tbody>
</table>
The average characters per minute typed was also calculated by session. Although the sessions were one-and-a-half hours long, not all of that time was spent typing because of rest breaks after each trial. Calculating characters per minute by session does not indicate any specific time period, but maintains the continuity of an entire day of practice.

The same five equations used to fit trials were tried with time periods:

\[
\begin{align*}
\text{CPM}_i &= B_0 + B_1P_i \quad \text{(Equation 1a)} \\
\text{CPM}_i &= B_0 + B_1/P_i + B_2/P_i^2 \quad \text{(Equation 2a)} \\
\text{CPM}_i &= B_0 + B_1P_i + B_2/P_i + B_3/P_i^2 \quad \text{(Equation 3a)} \\
\text{CPM}_i &= B_0 + B_1\ln(P_i) \quad \text{(Equation 4a)} \\
\text{CPM}_i &= e^{B_0} P_i^{B_1} \quad \text{(Equation 5a)}
\end{align*}
\]

where CPM\(_i\) is the characters per minute typed on the i-th time period (dependent variable), P\(_i\) is the i-th time period (30, 40, 50 or 60 minute periods or days) and B's are fitted coefficients.

Table 8 lists the R\(^2\) values found for all equations for each time period by subject. The equations CPM\(_i\) = B\(_0\) + B\(_1\)P\(_i\) + B\(_2\)/P\(_i\) + B\(_3\)/P\(_i\)^2 and CPM\(_i\) = e^{B_0} P_i^{B_1} (Log-Log) provided the best fit for every time increment considered. Their R\(^2\) values are equal to at least 0.96 in every case. Appendix E contains the graphs of actual performance and predictions using both CPM\(_i\) = B\(_0\) + B\(_1\)P\(_i\) + B\(_2\)/P\(_i\) + B\(_3\)/P\(_i\)^2 and CPM\(_i\) = e^{B_0} P_i^{B_1} for all time increments and subjects.

4.5 Subjective Ratings of Performance.

At the end of the every fifth session the subjects were asked to rate their performance on a 0 to 9 scale (shown previously in Figure 19). The ratings for
Table 8. Summary of R-Squared Values for All Functions Considered When Time Increment is the Regressor Variable. 30, 40, 50, and 60 Minute Increments and Sessions are Used.

### 30 Minute Period (approximately 70 observations)

<table>
<thead>
<tr>
<th></th>
<th>CPMi = Bo + B1*Pi</th>
<th>CPMi = Bo + B1/Pl + B2/Pi^2</th>
<th>CPMi = Bo + Bo*P+1 + B1/Pl + B2/Pi^2</th>
<th>CPMi = Bo + B1*Ln(Pl)</th>
<th>CPMi = e^Bo*(Pl*B1) (log-log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>0.978</td>
<td>0.624</td>
<td>0.984</td>
<td>0.868</td>
<td>0.965</td>
</tr>
<tr>
<td>Subject 2</td>
<td>0.893</td>
<td>0.802</td>
<td>0.982</td>
<td>0.966</td>
<td>0.987</td>
</tr>
<tr>
<td>Subject 3</td>
<td>0.896</td>
<td>0.778</td>
<td>0.978</td>
<td>0.966</td>
<td>0.989</td>
</tr>
<tr>
<td>Subject 4</td>
<td>0.880</td>
<td>0.812</td>
<td>0.979</td>
<td>0.973</td>
<td>0.989</td>
</tr>
<tr>
<td>Subject 5</td>
<td>0.892</td>
<td>0.780</td>
<td>0.973</td>
<td>0.960</td>
<td>0.986</td>
</tr>
<tr>
<td>Average</td>
<td>0.908</td>
<td>0.759</td>
<td>0.979</td>
<td>0.947</td>
<td>0.983</td>
</tr>
</tbody>
</table>

### 40 Minute Period (approximately 54 observations)

<table>
<thead>
<tr>
<th></th>
<th>CPMi = Bo + B1*Pi</th>
<th>CPMi = Bo + B1/Pl + B2/Pi^2</th>
<th>CPMi = Bo + Bo*P+1 + B1/Pl + B2/Pi^2</th>
<th>CPMi = Bo + B1*Ln(Pl)</th>
<th>CPMi = e^Bo*(Pl*B1) (log-log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>0.980</td>
<td>0.672</td>
<td>0.985</td>
<td>0.871</td>
<td>0.964</td>
</tr>
<tr>
<td>Subject 2</td>
<td>0.896</td>
<td>0.842</td>
<td>0.986</td>
<td>0.971</td>
<td>0.988</td>
</tr>
<tr>
<td>Subject 3</td>
<td>0.894</td>
<td>0.824</td>
<td>0.981</td>
<td>0.973</td>
<td>0.991</td>
</tr>
<tr>
<td>Subject 4</td>
<td>0.878</td>
<td>0.859</td>
<td>0.983</td>
<td>0.979</td>
<td>0.987</td>
</tr>
<tr>
<td>Subject 5</td>
<td>0.893</td>
<td>0.823</td>
<td>0.975</td>
<td>0.962</td>
<td>0.986</td>
</tr>
<tr>
<td>Average</td>
<td>0.908</td>
<td>0.804</td>
<td>0.982</td>
<td>0.951</td>
<td>0.983</td>
</tr>
</tbody>
</table>

### 50 Minute Period (approximately 43 observations)

<table>
<thead>
<tr>
<th></th>
<th>CPMi = Bo + B1*Pi</th>
<th>CPMi = Bo + B1/Pl + B2/Pi^2</th>
<th>CPMi = Bo + Bo*P+1 + B1/Pl + B2/Pi^2</th>
<th>CPMi = Bo + B1*Ln(Pl)</th>
<th>CPMi = e^Bo*(Pl*B1) (log-log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>0.981</td>
<td>0.716</td>
<td>0.986</td>
<td>0.878</td>
<td>0.968</td>
</tr>
<tr>
<td>Subject 2</td>
<td>0.898</td>
<td>0.873</td>
<td>0.989</td>
<td>0.975</td>
<td>0.989</td>
</tr>
<tr>
<td>Subject 3</td>
<td>0.896</td>
<td>0.850</td>
<td>0.981</td>
<td>0.975</td>
<td>0.989</td>
</tr>
<tr>
<td>Subject 4</td>
<td>0.882</td>
<td>0.883</td>
<td>0.986</td>
<td>0.982</td>
<td>0.986</td>
</tr>
<tr>
<td>Subject 5</td>
<td>0.894</td>
<td>0.861</td>
<td>0.979</td>
<td>0.966</td>
<td>0.987</td>
</tr>
<tr>
<td>Average</td>
<td>0.910</td>
<td>0.837</td>
<td>0.984</td>
<td>0.959</td>
<td>0.984</td>
</tr>
</tbody>
</table>
### Table 8. (continued)

#### 60 Minute Period

(approximately 36 observations)

<table>
<thead>
<tr>
<th></th>
<th>CPMi = Bo + B1*Pi</th>
<th>CPMi = Bo + B1/Pl + B2/Pl^2</th>
<th>CPMi = Bo + Bo*Pl + B1/Pl + B2/Pl^2</th>
<th>CPMi = Bo + B1*Ln(Pl)</th>
<th>CPMi = e^Bo*(Pl^B1) (log-log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>0.982</td>
<td>0.749</td>
<td>0.987</td>
<td>0.885</td>
<td>0.973</td>
</tr>
<tr>
<td>Subject 2</td>
<td>0.897</td>
<td>0.896</td>
<td>0.991</td>
<td>0.980</td>
<td>0.988</td>
</tr>
<tr>
<td>Subject 3</td>
<td>0.897</td>
<td>0.874</td>
<td>0.984</td>
<td>0.979</td>
<td>0.990</td>
</tr>
<tr>
<td>Subject 4</td>
<td>0.884</td>
<td>0.900</td>
<td>0.987</td>
<td>0.984</td>
<td>0.984</td>
</tr>
<tr>
<td>Subject 5</td>
<td>0.897</td>
<td>0.885</td>
<td>0.983</td>
<td>0.974</td>
<td>0.989</td>
</tr>
<tr>
<td>Average</td>
<td>0.911</td>
<td>0.861</td>
<td>0.986</td>
<td>0.960</td>
<td>0.985</td>
</tr>
</tbody>
</table>

#### By Day

(39 observations)

<table>
<thead>
<tr>
<th></th>
<th>CPMi = Bo + B1*day</th>
<th>CPMi = Bo + B1/day + B2/day*2</th>
<th>CPMi = Bo + B1<em>day + B2/day + B3/day</em>2</th>
<th>CPMi = Bo + B1*Ln(day)</th>
<th>CPMi = e^Bo*(day^B1) (log-log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>0.954</td>
<td>0.765</td>
<td>0.983</td>
<td>0.931</td>
<td>0.988</td>
</tr>
<tr>
<td>Subject 2</td>
<td>0.817</td>
<td>0.892</td>
<td>0.986</td>
<td>0.979</td>
<td>0.976</td>
</tr>
<tr>
<td>Subject 3</td>
<td>0.778</td>
<td>0.910</td>
<td>0.984</td>
<td>0.974</td>
<td>0.975</td>
</tr>
<tr>
<td>Subject 4</td>
<td>0.821</td>
<td>0.918</td>
<td>0.990</td>
<td>0.993</td>
<td>0.964</td>
</tr>
<tr>
<td>Subject 5</td>
<td>0.814</td>
<td>0.889</td>
<td>0.992</td>
<td>0.977</td>
<td>0.980</td>
</tr>
<tr>
<td>Average</td>
<td>0.837</td>
<td>0.875</td>
<td>0.985</td>
<td>0.971</td>
<td>0.977</td>
</tr>
</tbody>
</table>

#### Average over Subjects

<table>
<thead>
<tr>
<th>Average R^2</th>
<th>CPMi = Bo + B1*Pi</th>
<th>CPMi = Bo + B1/Pl + B2/Pl^2</th>
<th>CPMi = Bo + Bo*Pl + B1/Pl + B2/Pl^2</th>
<th>CPMi = Bo + B1*Ln(Pl)</th>
<th>CPMi = e^Bo*(Pl^B1) (log-log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Min</td>
<td>0.908</td>
<td>0.759</td>
<td>0.979</td>
<td>0.947</td>
<td>0.983</td>
</tr>
<tr>
<td>40 Min</td>
<td>0.908</td>
<td>0.804</td>
<td>0.982</td>
<td>0.951</td>
<td>0.983</td>
</tr>
<tr>
<td>50 Min</td>
<td>0.910</td>
<td>0.837</td>
<td>0.984</td>
<td>0.959</td>
<td>0.984</td>
</tr>
<tr>
<td>60 Min</td>
<td>0.911</td>
<td>0.861</td>
<td>0.986</td>
<td>0.960</td>
<td>0.985</td>
</tr>
<tr>
<td>By Day</td>
<td>0.837</td>
<td>0.875</td>
<td>0.985</td>
<td>0.971</td>
<td>0.977</td>
</tr>
<tr>
<td>Avg of Avg</td>
<td>0.895</td>
<td>0.827</td>
<td>0.983</td>
<td>0.958</td>
<td>0.982</td>
</tr>
</tbody>
</table>

CPMi = Characters per Minute on the i-th time period
Bo, B1, B2, and B3 are fitted coefficients
Pl = Time Period
all the subjects are shown in Table 9. The average characters per minute typed on every fifth day is matched with the subjective ratings. No further analysis was performed on the subjective ratings.

4.6 Fastest Speed Attained by the Subjects.

For most of the experiment, the subjects were presented trials which were composed of randomly ordered characters. However, during the final session, subjects were presented trials which were composed of a string of six characters repeated 84 times (see Section 3.3.3). In Table 10, the fastest typing speed on the repetition trials is compared with the fastest speed attained on the randomized trials. The mean of the fastest speed attained on the random trials (170.1 CPM) was compared with the mean of the fastest speed on the repeated character string trial (175.3) using a t-test; the difference between the two means was not significant (p > 0.20).

4.7 Prediction of Learning with Less Than all Data Points.

The analysis to this point has focused on the prediction of learning for individuals where all actual performance points were used in the regression. It is desirable to be able to predict an accurate performance curve of long term learning using only a few initial performance points.

The coefficients of the equation $CPM_i = e^{B0T_iB1}$ ($T_i$ = trials) were determined for each subject when only the performance in either the first 5, 10, 15, 20, 25, 50, 75, 100, 125, 150, 175, and 200 trials was used in the regression. Figure 30 shows the actual performance by trial and the predictions when either 25, 50, 100, 150, 200, or all points were used in the regression for
Table 9. Ratings Ranging From 0 to 9 Given by the Subjects Each Week Assessing Their Progress and Corresponding Performance.

<table>
<thead>
<tr>
<th>Day</th>
<th>Subject 1 Rating</th>
<th>Avg. CPM</th>
<th>Subject 1 Rating</th>
<th>Avg. CPM</th>
<th>Subject 2 Rating</th>
<th>Avg. CPM</th>
<th>Subject 3 Rating</th>
<th>Avg. CPM</th>
<th>Subject 4 Rating</th>
<th>Avg. CPM</th>
<th>Subject 5 Rating</th>
<th>Avg. CPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4</td>
<td>53.3</td>
<td>4</td>
<td>84.7</td>
<td>4.5</td>
<td>96.8</td>
<td>5.5</td>
<td>67.6</td>
<td>4</td>
<td>71.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>74.2</td>
<td>5</td>
<td>118.8</td>
<td>6</td>
<td>122.4</td>
<td>7</td>
<td>89.0</td>
<td>5</td>
<td>101.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>5.5</td>
<td>89.5</td>
<td>5</td>
<td>124.8</td>
<td>6.5</td>
<td>127.8</td>
<td>8</td>
<td>106.2</td>
<td>4</td>
<td>96.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>6.75</td>
<td>113.8</td>
<td>6</td>
<td>136.3</td>
<td>6.5</td>
<td>143.8</td>
<td>8</td>
<td>118.3</td>
<td>5</td>
<td>112.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>8</td>
<td>133.0</td>
<td>6</td>
<td>147.2</td>
<td>7</td>
<td>156.8</td>
<td>8.3</td>
<td>128.1</td>
<td>5.5</td>
<td>126.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>8.5</td>
<td>144.9</td>
<td>7</td>
<td>162.9</td>
<td>7.5</td>
<td>167.5</td>
<td>9</td>
<td>130.6</td>
<td>5</td>
<td>119.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>8.8</td>
<td>156.0</td>
<td>7</td>
<td>165.8</td>
<td>7.5</td>
<td>170.4</td>
<td>9</td>
<td>136.0</td>
<td>6</td>
<td>136.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>8.9</td>
<td>170.9</td>
<td>8</td>
<td>174.8</td>
<td>8</td>
<td>173.1</td>
<td>9</td>
<td>144.2</td>
<td>7.5</td>
<td>147.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rating ranges from 0 to 9

Avg. CPM = The average characters per minute typed over the entire day
Table 10. Fastest Speed Attained on Randomized and Repetitive Trials.

<table>
<thead>
<tr>
<th></th>
<th>Peak Keying Speed (Characters per Minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fastest attained in Randomized Trials</td>
</tr>
<tr>
<td>Subject 1</td>
<td>177.9</td>
</tr>
<tr>
<td>Subject 2</td>
<td>186.3</td>
</tr>
<tr>
<td>Subject 3</td>
<td>180.6</td>
</tr>
<tr>
<td>Subject 4</td>
<td>150.6</td>
</tr>
<tr>
<td>Subject 5</td>
<td>155.2</td>
</tr>
</tbody>
</table>
Figure 30. Log-Log Regressions Using only the first 25, 50, 100, 150, and 200 Points, Subject 1
subject 1. (Regressions with 5, 10, 15, 20, 75, 125, and 175 points were also calculated, but are not shown due to space limitations.) To determine how accurately each equation fits the actual data, the mean squared error (MSE) was calculated for all regressions considered. The squared error (predicted CPM minus actual CPM, squared) was calculated for all the trials that each subject completed. All squared errors (for example 487 squared errors for subject 1) were averaged to obtain the MSE. The smaller the MSE, the more closely the equation predicts the actual performance over the entire range considered. Figure 31 shows the mean squared error as a function of the number of initial points used to calculate the regression for Subject 1. Figures 32, 34, 36, and 38 show the prediction equations for subjects 2, 3, 4, and 5 respectively. Figures 33, 35, 37, and 39 plot the mean squared error as a function of initial points used to calculate the regression for subjects 2, 3, 4, and 5 respectively.

The mean squared errors are shown in Table 11 for all subjects and the number of initial points used to fit the Log-Log equation. The data from Table 11 (MSE’s for all subjects) are graphed in Figure 40.

It is possible that one of the other original functions considered (e.g., $\text{CPM}_i = B_0 + B_1 \ln(T_i)$) would be effective in predicting final performance from only a few initial points even though it did not provide good fits using all the data points. For subject 2, the following three equations were also used to predict performance when only the first 25, 50, 100, 150, and 200 data points were included to calculate the coefficients.

\[
\text{CPM}_i = B_0 + B_1/T_i + B_2/T_i^2
\]
\[
\text{CPM}_i = B_0 + B_1 T_i + B_2/T_i + B_3/T_i^2
\]
Figure 31. MSE for Log-Log Regressions Using Only a Few Initial Points, Subject 1.
Figure 32. Log-Log Regressions Using only the first 25, 50, 100, 150, and 200 Points, Subject 2.
Figure 33. MSE for Log-Log Regressions Using Only a Few Initial Points, Subject 2
Figure 35. MSE for Log-Log Regressions Using Only a Few Initial Points, Subject 3
Figure 36. Log-Log Regressions Using only the first 25, 50, 100, 150, and 200 Points, Subject 4
Figure 37. MSE for Log-Log Regressions Using Only a Few Initial Points, Subject 4
Figure 38. Log-Log Regressions Using only the first 25, 50, 100, 150, and 200 Points, Subject 5
Figure 39. MSE for Log-Log Regressions Using Only a Few Initial Points, Subject 5
Table 11. Mean Squared Error for Log-Log Functions Fit Using Only Some of the Initial Performance Data Points.

<table>
<thead>
<tr>
<th>Number of Initial Points Used in Regression</th>
<th>Mean Squared Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subject 1</td>
</tr>
<tr>
<td>25</td>
<td>1471.4</td>
</tr>
<tr>
<td>50</td>
<td>1130.6</td>
</tr>
<tr>
<td>75</td>
<td>1147.2</td>
</tr>
<tr>
<td>100</td>
<td>639.9</td>
</tr>
<tr>
<td>125</td>
<td>515.4</td>
</tr>
<tr>
<td>150</td>
<td>337.4</td>
</tr>
<tr>
<td>175</td>
<td>224.9</td>
</tr>
<tr>
<td>200</td>
<td>133.0</td>
</tr>
<tr>
<td>487</td>
<td>43.9</td>
</tr>
<tr>
<td>509</td>
<td></td>
</tr>
<tr>
<td>516</td>
<td></td>
</tr>
<tr>
<td>622</td>
<td></td>
</tr>
<tr>
<td>636</td>
<td></td>
</tr>
</tbody>
</table>
\[ CPM_i = B_0 + B_1 \ln(T_i) \]

Figure 41 shows the regression equations obtained for the function \( CPM_i = B_0 + B_1/T_i + B_2/T_i^2 \); the mean squared error for each equation is graphed in Figure 42. The predictions from \( CPM_i = B_0 + B_1T_i + B_2/T_i + B_3/T_i^2 \) are shown in Figure 43 and the mean squared error for each fit in Figure 44. Finally, the fit of \( CPM_i = B_0 + B_1\ln(T_i) \) using only some of the initial data points is graphed in Figure 45 and the mean squared error in Figure 46. For subject 2, the mean squared errors for the four equations considered are listed in Table 12 by number of points used to fit the coefficients. It is clear from Table 12 and Figures 42, 44, and 46 that only the Log-Log function can accurately predict the entire learning curve and final performance from a few initial data points.

### 4.8 Chord Analyses.

Response times for each of the 18 chords were recorded for all trials for every subject. The average response times for each chord by trial were plotted for all chords for the first 487 trials -- see Appendix F. The first 487 trials are used because these were completed by all five subjects.

An analysis of variance was performed on the chord data for the last 20 trials, i.e. the trials 468 to 487. Response time was modeled on a within-subject design of trial and chord. The chord effect and trial X chord effect were both significant at \( p < 0.0001 \). A post-hoc analysis (Student-Newman-Keuls test) was performed on the chord effect to determine which chords were significantly fastest. Table 13 lists each chord, its average response time, and its relative statistical significance. No post-hoc analysis was performed on the trial X chord data, owing to the large number of comparisons (360).
Figure 41. Subject 2, $Bo + B1/Ti + B2/Ti^2$ Regressions Using Only the First 25, 50, 100, 150, and 200 Points.
Figure 42. Subject 2, MSE for Bo+B1/Ti+B2/Ti^2 Regressions Using Only a Few Initial Points.
Figure 43. Subject 2, $Bo+B1^*Ti+B2/Ti+B3/Ti^2$ Regressions Using Only the First 25, 50, 100, 150, and 200 Points.
Figure 44. Subject 2, MSE for $Bo+B1^{*}Ti+B2/Ti+B3/Ti^2$ Using Only a Few Initial Points.
Figure 46. Subject 2, MSE for $B_0 + B_1 \ln(T_i)$ Regressions Using Only a Few Initial Points.
Table 12. Mean Squared Error for Four Equations Fit Using Only Some of the Initial Performance Data Points. For Subject 2 Only.

<table>
<thead>
<tr>
<th>Equation</th>
<th>25</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CPM_i = Bo + B1 \times Ti + B2/Ti + B3/Ti^2 )</td>
<td>21860.1</td>
<td>71309.7</td>
<td>14519.7</td>
<td>2904.1</td>
<td>1284.4</td>
<td>68.8</td>
</tr>
<tr>
<td>( CPM_i = Bo + B1/Ti + B2/Ti^2 )</td>
<td>4815.6</td>
<td>3056.1</td>
<td>1580.5</td>
<td>1376.6</td>
<td>1063.7</td>
<td>405.5</td>
</tr>
<tr>
<td>( CPM_i = Bo + B1 \times \ln(Ti) )</td>
<td>1989.3</td>
<td>547.8</td>
<td>170.9</td>
<td>174.1</td>
<td>117.8</td>
<td>44.1</td>
</tr>
<tr>
<td>( CPM_i = (e^Bo) \times (Ti^B1) )</td>
<td>875.3</td>
<td>43.1</td>
<td>80.3</td>
<td>57.3</td>
<td>49.3</td>
<td>40.9</td>
</tr>
</tbody>
</table>

CPMi = Characters per Minute
Bo, B1, B2, and B3 are fitted coefficients
Ti = Trials
Table 13. Chord Response Times (in ms) Averaged Over Trials 468 to 487, the Last 20 Trials Performed by All Subjects. (Means with the same letters are not significantly different)

<table>
<thead>
<tr>
<th>Chord</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>SNK Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>325.0</td>
<td>139.7</td>
<td>A</td>
</tr>
<tr>
<td>24</td>
<td>329.0</td>
<td>125.7</td>
<td>A B</td>
</tr>
<tr>
<td>14</td>
<td>350.5</td>
<td>144.5</td>
<td>A B C</td>
</tr>
<tr>
<td>36</td>
<td>359.2</td>
<td>138.0</td>
<td>A B C</td>
</tr>
<tr>
<td>35</td>
<td>361.8</td>
<td>148.4</td>
<td>A B C</td>
</tr>
<tr>
<td>28</td>
<td>364.6</td>
<td>150.3</td>
<td>A B C</td>
</tr>
<tr>
<td>26</td>
<td>368.3</td>
<td>148.3</td>
<td>A B C D</td>
</tr>
<tr>
<td>45</td>
<td>368.9</td>
<td>145.8</td>
<td>A B C D</td>
</tr>
<tr>
<td>46</td>
<td>371.0</td>
<td>160.6</td>
<td>A B C D</td>
</tr>
<tr>
<td>68</td>
<td>371.4</td>
<td>176.2</td>
<td>A B C D</td>
</tr>
<tr>
<td>23</td>
<td>372.9</td>
<td>140.7</td>
<td>B C D</td>
</tr>
<tr>
<td>15</td>
<td>375.5</td>
<td>168.9</td>
<td>B C D</td>
</tr>
<tr>
<td>17</td>
<td>378.5</td>
<td>160.0</td>
<td>C D</td>
</tr>
<tr>
<td>57</td>
<td>380.2</td>
<td>171.4</td>
<td>C D</td>
</tr>
<tr>
<td>16</td>
<td>381.0</td>
<td>168.1</td>
<td>C D</td>
</tr>
<tr>
<td>25</td>
<td>399.4</td>
<td>177.7</td>
<td>C D</td>
</tr>
<tr>
<td>37</td>
<td>413.4</td>
<td>167.2</td>
<td>D</td>
</tr>
<tr>
<td>48</td>
<td>414.3</td>
<td>175.3</td>
<td>D</td>
</tr>
</tbody>
</table>
4.9 Analysis of Average Performance of All Subjects.

To this point the analysis was focused on predicting performance of individual subjects. It is also of interest to evaluate the ability of the functions to predict the combined subjects’ data as well as the average typing speed.

4.9.1 Prediction of All Subjects Performance.

Using regressions to predict combined data of the subjects differs from predicting average performance; each trial has five values (one from each subject) whereas an average prediction has only one point for each trial. The five functions considered for individual data were also used to predict all subjects’ data:

\[
\begin{align*}
\text{CPM}_i &= B_0 + B_1 T_i \\
\text{CPM}_i &= B_0 + B_1/T_i + B_2/T_i^2 \\
\text{CPM}_i &= B_0 + B_1 T_i + B_2/T_i + B_3/T_i^2 \\
\text{CPM}_i &= B_0 + B_1 \ln(T_i) \\
\text{CPM}_i &= e^{B_0 T_i^{B_1}}
\end{align*}
\]

(Equation 1) (Equation 2) (Equation 3) (Equation 4) (Equation 5)

These equations were only fit on the first 487 trials - those that included all subjects. The \( R^2 \) values for each function are listed in Table 14. The following Log-Log equation provided the best fit (\( R^2 = 0.843 \)):

\[
\text{CPM}_i = 33.115 \cdot T_i^{0.251}
\]

The actual data points of all subjects and the plotted equation are shown in Figure 47.
Table 14. Summary of R-Squared Values for All Functions Considered for Average of the Subjects and All Subjects' Performance

<table>
<thead>
<tr>
<th>Equation</th>
<th>All Subjects</th>
<th>Avg. of Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CPMi = Bo + B1 \cdot Ti$</td>
<td>0.747</td>
<td>0.883</td>
</tr>
<tr>
<td>$CPMi = Bo + B1/Ti + B2 \cdot (1/Ti^2)$</td>
<td>0.351</td>
<td>0.457</td>
</tr>
<tr>
<td>$CPMi = Bo + B1 \cdot Ti + B2 \cdot (1/Ti) + B3 \cdot (1/Ti^2)$</td>
<td>0.799</td>
<td>0.951</td>
</tr>
<tr>
<td>$CPMi = Bo + B1 \cdot \ln(Ti)$</td>
<td>0.791</td>
<td>0.956</td>
</tr>
<tr>
<td>$CPMi = \exp(Bo) \cdot (Ti^B1)$</td>
<td>0.843</td>
<td>0.991</td>
</tr>
</tbody>
</table>

CPMi = Characters per Minute on the i-th Trial

Ti = Trial

Bo, B1, B2, and B3 are fitted coefficients
Figure 47. Log-Log Prediction and Actual Performance, All Subjects' Data.
4.9.2 **Prediction of Average Performance.**

The average typing speed and its standard deviation were calculated for the trials completed by all five subjects (up to trial 487). The same five equations used to predict individual performance were considered to fit average performance. Table 14 lists the $R^2$ values for each function. The following Log-Log equation provided the best fit of the data ($R^2 = 0.991$):

$$CPM_i = 34.467 \times T_i^{0.244}$$

Figure 48 shows the average characters per minute typed, the prediction of the average using the above equation, and the average plus and minus one standard deviations.
CPM = 34.467 \cdot (\text{Trial}^{0.244})

Figure 48. Log-Log Prediction, Actual Average Performance, and + and - 1 Standard Deviation of the Average of All Subjects.
5. DISCUSSION

The goals of the experiment were to find answers to questions that have not been fully addressed in the literature. This study provided information on what function best predicts learning, the best predictors of performance, and criterion of peak keying speed. The study did not address all the questions raised in the literature review; for example, the relationship of character set size versus time to maximal speed is important, but was not investigated.

5.1 Speed - Accuracy Performance.

Providing feedback to the subjects at the end of each trial seemed to be very effective in controlling speed and accuracy tradeoffs. All the subjects had an average accuracy greater than 97% over the entire experiment. In addition, the subjects generally set goals for themselves such as finish a trial in less than five minutes or reach 100 characters per minute. By providing feedback of performance, there seemed to be natural performance goals throughout the experiment for which the subjects aimed.

The subjects probably did not make adjustments in their speed and accuracy criteria after every trial, but more likely made adjustments after perceiving a trend in either speed or accuracy performance. For example, if a subject's accuracy level for a particular trial fell below 97%, that person probably did not immediately slow down on the next trial. However, if accuracy performance on many consecutive trials was below 97%, the subject probably maintained speed but tried to increase accuracy. Overall, the method of providing immediate feedback to the subjects on speed and accuracy appeared
effective in motivating the subjects and controlling some of the error associated with speed accuracy tradeoffs.

5.2 Using Trials to Predict Performance.

One goal of this study was to find an equation which described the learning or performance progress on a keyboarding task. The following five candidate functions were fit to individual performance curves.

\[
\begin{align*}
CPM_i &= B_0 + B_1 T_i \quad \text{(Equation 1)} \\
CPM_i &= B_0 + B_1 T_i + B_2 T_i^2 \quad \text{(Equation 2)} \\
CPM_i &= B_0 + B_1 T_i + B_2 T_i + B_3 T_i^2 \quad \text{(Equation 3)} \\
CPM_i &= B_0 + B_1 \ln(T_i) \quad \text{(Equation 4)} \\
CPM_i &= e^{B_0} T_i^{B_1} \quad \text{(Equation 5)}
\end{align*}
\]

where \( CPM_i \) is the characters per minute typed on the \( i \)-th trial (dependent variable), \( T_i \) is the \( i \)-th trial, and \( B_0 \) and \( B_1 \) are fitted coefficients.

Only equations that predicted performance in a monotonically increasing fashion were considered. Actual performance on a keyboarding task is not always increasing with each additional trial of practice; however, there is a general trend of improvement with practice in learning a skill. A Log-Log equation of the form \( CPM_i = e^{B_0} T_i^{B_1} \) (where \( CPM_i \) is performance on the \( i \)-th trial or hour, \( T_i \) is the \( i \)-th trial or hour of practice, and \( B_0 \) and \( B_1 \) are fitted coefficients) described each subject’s performance most accurately. The Log-Log equation had an average \( R^2 \) of 0.956 when using trials as the regressor variable. An important characteristic of this type of equation is that it does not
reach an asymptote, and therefore does not predict a maximal keying speed. The only equation considered which predicts an asymptote \(\text{CPM}_i = B_0 + B_1/T_i + B_2/T_i^2\) did not even account for 50% of the variance (average \(R^2 = 0.431\)).

Overall, the Log-Log function provided the best description of subject performance on the keyboarding task up to the first 60 hours of practice when trials are the predictor variables. The ability of the equation to predict beyond that point is unknown because there are no actual performance data for comparison with the predictions. However, from Figures 24 to 28 it appears that the subjects did not reach peak performance (i.e., a stable, non-increasing value) in this experiment.

5.2.1 Coefficients of the Log-Log Equation.

It appears that the shapes of the Log-Log curves (performance predictions) for subjects 2 to 5 are very similar, as shown previously in Figure 29. However, the performance prediction of subject 1 varies significantly from the predictions for the other four subjects. The predictions for subjects 2 and 3 are nearly identical, as are the predictions for subjects 4 and 5. Subjects’ 2 and 3 performance predictions seem to differ from subjects 4 and 5 by only a constant. It was hypothesized that one or both of the coefficients for subject 1 were significantly different from the other subjects causing the different shape of the prediction curve. However, after using a t-test to compare the values of the coefficients, it was found that all the \(B_0\) coefficients were significantly different from each other, and all \(B_1\) comparisons except one were significantly different, as shown previously in Table 6. The reason for so many significant differences
in the coefficients is that the t-tests were so powerful because of the large number of observations for each subject.

5.2.2 Prediction of Peak Keying Speed.

While the Log-Log function predicts the actual progress of the subjects very well, by its nature it does not approach a peak value asymptote. Four techniques can be used to estimate each subject's peak performance. First, a large number of trials chosen to represent the upper limit of practice can be entered into the Log-Log equation. For example, 5,000 trials might be assumed to be a long enough training period for a person to reach a peak keying speed. For subject 3, this leads to a speed of 265 characters per minute \( CPM_{5000} = 48.231 \times 5000^{0.199} = 265 \).

The second method uses the slope of the Log-Log function to determine peak keying speed. Although the Log-Log function never approaches an asymptote, its slope decreases as trial numbers increase. Slope is equal to the first derivative of the performance function, \( CPM_i = 48.231 \times T_i^{0.199} \). The first derivative of this equation is as follows:

\[
\frac{d(CPM_i)}{dT_i} [\text{slope}] = (0.199)(48.231) \times T_i^{-0.801} = 9.6 \times T_i^{-0.801}
\]

Thus, a given slope could be associated with top speed, the trial number determined when this slope occurs, and finally that trial number could be used to calculate maximal performance. For example, it may be assumed that when the slope decreases to 0.025 CPM/Trial, a person has effectively reached peak performance. For subject 3, a slope of 0.025 CPM/Trial occurs at trial 1684 (solving for \( T_i \) when 0.025 = 9.6 \( \times T_i^{-0.801} \)). At trial 1684, the Log-Log equation
predicts a speed of 212 characters per minute \( (\text{CPM}_{1684} = 48.231 \times 1684^{0.199} = 212) \).

The third technique to predict top speed involves using the function \( \text{CPM}_i = B_0 + B_1/T_i + B_2/T_i^2 \) as suggested by Bittner (1991). He assumed that the equation \( Y_i = B_0 + B_1/T_i + B_2/T_i^2 \) can predict peak performance, where \( Y_i \) is the \( i \)-th trial performance, \( T_i \) is the \( i \)-th trial, and \( B_0, B_1, \) and \( B_2 \) are fitted coefficients. As the number of trials increases the magnitude of the last two terms decreases very rapidly (\( B_1/T_i \) and \( B_2/T_i^2 \)) and \( B_0 \) estimates peak performance; it is the only function of all functions considered that will reach an asymptote. However, this formula does not predict the performance progress of the subjects very well (all \( R^2 \) are less than 0.5 as shown in Table 4); thus, \( B_0 \) can not be considered an accurate prediction of the fastest keying speed.

The function appears not to predict final performance well because of the steepness of the initial learning curve; thus, it underestimates peak performance, see Figure 21 for subject 2. If several of the early points are deleted from the regression, this function might predict a more accurate asymptote. As an example, the formula \( \text{CPM}_i = B_0 + B_1/T_i + B_2/T_i^2 \) was fit to the data of subject 3 ignoring the first 100 data points. It appears that most of the steep portion of the learning curve is eliminated by ignoring the first 100 points, see Figure 49. The fit of the remaining 536 points yields the equation \( \text{CPM}_i = 195.7 - 16,199(1/T_i) + 919,625(1/T_i^2) \) which has an \( R^2 \) of 0.863 and predicts a peak performance of 195.7 characters per minute.

The fourth technique used to predict peak performance employs only the final trials. These trials were composed of a string of six characters repeated 84 times (see Section 3.3.3). It was felt that if keying the string became a highly
automated motor program (with minimal response times), the performance on these trials would represent peak keying speed. However, two of the subjects typed faster in the random trials than in the repeated character string trial, as shown previously in Table 10. In addition, the means of the fastest speeds attained on randomized and repetitive trials were not significantly different which indicates that the repetitive trials, in fact, were not a good indication of peak keying performance.

Of the four techniques, using the equation \( CPM_i = B_0 + B_1/T_i + B_2/T_i^2 \) (without initial trials) might provide the best method for predicting peak performance. This equation provides a much better predictor of actual performance if initial performance points are ignored; the \( R^2 \) values and predicted peak performance for each subject are shown in Table 15. This equation, without the 100 initial trials, predicts peak (asymptotic) performance which was not attained by any of the subjects on the randomized trials (comparing Table 15 with previously shown Table 10). The major difficulty with this approach is to determine how many of the original points should be left out of the regression.

Assuming a large amount of practice time, assuming a minimal slope, or using the repeated string trials do not seem to be suitable methods to use to predict peak performance. By what criteria could the number of trials be chosen and considered the upper limit of practice; should it be 2000, 5000, 10000, or more trials? The same dilemma arises when trying to assume a minimal slope as the stopping point of improvement.
Table 15. Values of $R^2$ and Peak Performance when Fitting the Equation $CPM_i = B_0 + B_1/T_i + B_2/T_i^2$ Without the First 100 Performance Points.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$R^2$</th>
<th>Predicted Peak (in CPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.940</td>
<td>196.8</td>
</tr>
<tr>
<td>2</td>
<td>0.854</td>
<td>197.7</td>
</tr>
<tr>
<td>3</td>
<td>0.863</td>
<td>195.7</td>
</tr>
<tr>
<td>4</td>
<td>0.870</td>
<td>158.8</td>
</tr>
<tr>
<td>5</td>
<td>0.759</td>
<td>161.1</td>
</tr>
</tbody>
</table>

where $CPM_i$ is the characters per minute typed on the $i$-th trial (dependent variable) and $T_i$ is the $i$-th trial of practice.
5.2.3 **Combined and Average Performance of All the Subjects.**

The Log-Log equation fit the combined and average performance of the subjects best. It was expected to fit best because it was the best at predicting each individual’s performance. The equation fit to the combined subjects' data probably had a high $R^2$ (0.843) because there were not more than five subjects' data. Kroemer (1990) and McMulkin and Kroemer (1991) did not find an equation which accurately fit combined subjects' data. This could be due either to the larger number of subjects (10 to 12) or the shorter training periods (3 to 12 hours).

5.3 **Predicting Performance from Time**

The average characters per minute entered by the subjects were calculated for 30, 40, 50, and 60 minute time periods and for sessions. Because the time periods were composed of entire trials, the average lengths of the 30, 40, 50, and 60 minute time periods were closer to 32, 42, 52, and 62 minutes respectively, shown previously in Table 7. It is not so important that the length of the time periods are factors of 10, but that the average length of the time increments is close to equal for all subjects. Inspection of Table 7 reveals that for all four time periods each subject had approximately the same average amount of practice.

After establishing the performance of the subjects over the time intervals, the same five equations used to predict performance from trials were fit to the time period data. The equations $CPM_i = B_0 + B_1P_i + B_2/P_i + B_3/P_i^2$ and $CPM_i = e^{B_0} P_i^{B_1}$ (a Log-Log equation) provided the best fits. $P_i$ is equal to 1, 2, 3,... not
30 minutes, 60 minutes, and so on. The general form of the Log-Log equation 
\( CPM_i = e^{B_0 P_i B_1} \) provided good fits for both repetition and time data.

It does not appear that changing the length of time increments has much 
effect on the ability to predict performance. Five different time increments were 
used as regressor variables: 30 minutes, 40 minutes, 50 minutes, 60 minutes, 
and total sessions (1.5 hours, not all this time was spent practicing). For the 
Log-Log function, the largest difference in \( R^2 \) values was only 0.008 (Table 8).

5.4 Subjective Ratings.

The subjective ratings could not be used in any analysis to predict 
performance of the subjects. The subjects probably found it difficult to rate their 
performance early in the experiment because they did not know what their final 
performance would be. At the beginning of the experiment, subjects might have 
simply chosen a middle rating and then gradually increased it until the end of 
the experiment. For this reason, the ratings that the subjects provided are not of 
an interval nature, but are instead at best an ordinal measure. The data of 
subjects four and five illustrate some of the problems with the subjective rating 
procedure, shown previously in Table 9. Subject four rated performance at a 
nine by day 30 but was clearly still improving over the following two weeks. 
Subject five rated performance at a four on day 5, then a five on day 10, and 
then back to a four on day 15. This subject probably felt the ratings of the initial 
two weeks were too high and then readjusted the scale for week three and 
started the rating at four again. Overall, little information could be extracted from 
the results of the subjective ratings.
5.5 Evaluation of Criteria to Predict Performance.

Part of the second goal of the experiment was to determine which criterion of the following three criteria could be used to predict keying speed: number of trials/repetitions, hours (or other time increments) of practice, and subjective opinion. The Log-Log equation, $CPM_i = e^{B_0 T_i B_1}$, provided the most accurate prediction of performance when considering two regressor variables, time and repetition. The average $R^2$ values using the Log-Log function for these two criteria were as follows:

Trials (504 repetitions per trial) \hspace{1cm} R^2 = 0.956

Time of Practice (average for all increments) \hspace{1cm} R^2 = 0.982

This gives further credence to the assertion that the Log-Log function describes the underlying progress of performance. It does not appear to matter much whether repetition or time of practice is used to predict performance. Although the equation $CPM_i = B_0 + B_1 P_i + B_2/P_i + B_3/P_i^2$ is effective when time increments constitute the regressor variable, it did not predict performance as well as the Log-Log equation when trials constitute the predictor variable. This indicates that the equation to describe performance remains the same when the predictor variable changes from trials to time. These findings contrast those of Thurstone (1919); he asserted that the function changed when time instead of repetition was used to describe performance progress. The Log-Log function continued to show flexibility with different levels of the time predictor. The fits of the Log-Log equation had fairly constant $R^2$ values across the five time increments considered.
Subjective opinion data, as elicited in this study, could not be used to predict performance due to the ordinal nature of the ratings. See Section 5.4 for further discussion.

5.6 The Concept of Peak Performance.

It is apparent from Figures 24 to 28 that the actual performance of the subjects did not approach an asymptote which could be considered the peak performance. The Log-Log equation, which provided a very good description of the actual performance does not predict an asymptote; it presumes continual improvement in performance which, however, becomes increasingly slow and gradual.

Both the actual performance observed and the prediction of the Log-Log equation seem to contradict the traditional presumption of learning - a slow increase in performance until gradually a upper limit is reached that can not be exceeded. It might be that there is no limit to performance improvement.

The response times of the keyboarding task of this study can be broken down into their components. First, the stimulus must be sensed by the subject, for example the number 8 is to be typed. Second, the sensed information must be transmitted through the (afferent) peripheral nervous system to the brain. Third, a decision must be made in the brain as to what response to make to the incoming stimulus. Fourth, the response signal must be transmitted along the (efferent) peripheral nervous system to muscles. Fifth, the ensuing movement of the fingers determines the "response time" and a character is typed. The third and fifth steps of the response are probably becoming faster with practice with most of the improvement likely to occur in the third step, the decision making
process. There may be a limitation to how quickly response decisions can become. However, that minimal decision time may never actually be reached.

5.7 Prediction of an Entire Curve from the Initial Data Points.

From a practical standpoint, to predict the performance of subjects, it is costly to gather over 500 data points. It is, therefore, of great interest to find out how many initial performance points are needed before an accurate learning curve can be predicted.

For subject 2, four different equations were fit to the actual data when only 25, 50, 100, 150, and 200 of the initial performance points were used in the regression. The mean squared error between the actual and predicted performance for all 20 cases (4 equations and 5 quantities of initial number of points used in the regression) was shown previously in Table 12. By perusing the information in Table 12, it becomes clear that the only function capable of accurately predicting the entire learning curve from the initial data points is a Log-Log function.

The remaining functions do not closely approximate learning or final performance. The Log-Log equation has a mean squared error which is at least an order of magnitude smaller that the other three functions when only 25, 50, 100, 150, or 200 initial data points are used in the regressions. Inspection of previously shown Figures 32, 41, 43 and 45 clearly indicates that only the Log-Log function predicts final performance effectively from regressions including only a few initial performance points. The other functions either predict too high a final performance \( CPM_i = B_0 + B_1T_i + B_2/T_i + B_3/T_i^2 \) or too low a final performance \( CPM_i = B_0 + B_1/T_i + B_2/T_i^2 \) and \( CPM_i = B_0 + B_1\ln(T_i) \).
It is difficult from a small sample size of five subjects to draw a definite conclusion about how many points are sufficient to accurately predict the entire performance curve using the Log-Log equation. The regression using all points is assumed to have the lowest mean squared error. Thus, the MSE of regressions using less points should be compared to the MSE of the all points regressions to determine its relative accuracy. For four of the subjects (2 through 5), the MSE is drastically reduced when the number of points used reaches 50, see Figure 40 and Table 11 shown previously. The MSE resulting from including more than 50 points is a fairly flat function for these four subjects. In contrast, subject 1 exhibited a much more modest decrease in MSE as the number of points included in the regression increased.

Overall, the Log-Log function proved to be the only equation able to predict the entire learning curve from a limited number of initial data points. Due to the small number of subjects, it is difficult to make assertions about the number of points needed with the Log-Log equation to capture the entire performance progress with a reasonably small mean squared error: as few as 50 initial points were needed for four of the five subjects (out of about 550 total points). However, when applying these findings, the amount of uncertainty that is acceptable needs to be determined which then points to the number of initial performance points needed.

5.8 Chord Analyses.

The average response times for each chord were calculated for the last 20 trials including all subjects, i.e., trials 468 to 487. Table 13, shown previously, lists the chords' average response times and relative ranking. The
major result of the chord analysis is that after over 400 trials of practice there are still chords that are significantly faster than others. However, significant differences found could be due to the large power of the tests. Each chord average response time consisted of 2800 observations (28 chords per trial X 20 trials X 5 subjects).

The chord analysis was based on practice due to repetition not amount of time because response times from trials 468 to 487 were used. For subject 1, these trials were the last ones completed, while for subjects 2 to 5 they were completed before the end of the experiment. The number of final trials to include in the analysis was limited to 20 for two reasons. First, chord performance was of interest after a large amount of practice. It was of interest to find if differential chord performance existed after a large amount of practice. Second, the last 20 trials include enough observations to obtain a representative average and standard deviation. It is possible that fewer number of final trials could be used for the analysis.

5.9 Further Research.

The results of this study point to several areas for future research and analysis. First, the trials were held constant at 504 characters. It would be interesting to investigate the effect of different trial lengths on the ability of the Log-Log function to predict performance. In the same way that variations of time increments were used with the Log-Log equation, number of repetitions per trial could be varied and accuracy of the Log-Log function analyzed.

Second, the performance points seem to have some autocorrelation. Performances of the subjects “bounced” about the Log-Log curve. Apparently,
series of points alternated between being higher and lower than the previous point. It might be possible to include an autocorrelation factor in the model of performance and then account for more of the variation.

Third, as mentioned in the literature review, there appears to be a relationship between number of characters that are learned and the steepness of performance progress. Research is needed on how the values of the coefficients in the Log-Log equation change with character set size. For example, faster keying speeds might have been obtained more quickly if this study had used 10 characters instead of 18.

Fourth, the subjective opinions were that were obtained in this study could not be correlated with performance. Perhaps other techniques of rating could be used to find a relationship between performance and subjective opinion about that performance.
6. REFERENCES


Appendix A

Example of a Test Trial
0/728+*0474*-S/S9.88+*08+<-876/8148T3T118S+724+S04+67-T7742
1609/T931677*+/29S.S.12T+88S+286877<-+9T/-7T+.69366831929610/5
*7926480.<-+9072+21S04/1T7S01/26.-**42/42+108S55+5.512S00+78*
203+*5S+S+6S+348-962--T+0T*8-S/-0.8T01/126S-7T*71T.<+T-*1/8
7T1+/-69+4/8*/9947/S<-84935<-45T/8/S0-.1T+060-8*<-2T+698/20
T3/T0S<-+S3T2++-52S93++71424S.*.<-79S83S+32*.+6T0450ST--/41T6
34.-23-T*301+/-4/T2T48.1/83ST9226S/7544./-62469++1+7-**-S914.
4S6.*+17-56<-134919*/765937/36967.+5530.09910+*936++5.+3+3
5**5*55333.3.5..555555

S represents "Subtotal"
T represents "Total"
. represents "decimal point"
<- represents "backspace"
Appendix B

Experimental Instructions
EXPERIMENTAL INSTRUCTIONS

The purpose of the study is to gather information about a newly designed keyboard, called the One-Hand Ternary Chord Keyboard (TCK). You are expected to participate for 40 one-and-a-half hour sessions. There will be one session a day, five days a week for eight weeks; sessions will be scheduled for the same time each day.

The first session will be the "learning phase" and the following 39 will be the "performance phase".

Learning Phase. In the first session, you will learn general facts about the One-Hand TCK and how to type characters with it. You should proceed through this section at your own pace, follow directions on the computer screen carefully, and consult the experimenter when suggested by the computer screen and also if you have any questions or problems.

You will learn to type the 10 numbers and 8 mathematical symbols during this session. To help you learn these characters, quizzes will be given at times to test your knowledge. Please, keep in mind that you are expected to memorize how to type these characters, and to type them with not more than 3% errors.

Performance Phase. In each one-and-a-half hour sessions, you will be given text files to type which will increase your speed. Follow the instructions displayed on the computer screen. Please keep errors down at 3%, but - - go for speed!

Keep in mind that the purpose of this experiment is to determine the highest typing speed that you can attain on the One-Hand TCK. During the sessions, please work to increase your speed and give the fastest performance you can. It is expected that you will have a general trend to increase your keying speed over the 40 sessions.

Once a week you will be asked to rate your performance on a 0 to 9 scale. You will still finish the full 40 sessions regardless of your ratings, but it is important to the experimenter how you feel you are progressing.

The computer program will explain a great deal about the TCK, so wait until you have proceeded though the INTRODUCTION to the learning section before asking any detailed questions you might have. Consult the experimenter at any time if there are any questions or problems.

Initials ________
Appendix C

Informed Consent Form
CONSENT FORM

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

The experimenters have 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 initialed.

I recognize the research team as Mark McMulkin, Graduate Research Assistant (231-5359) and Dr. K.H.E. Kroemer, Principal Investigator (231-5677).

I understand that they 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 medical consultants 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, of by VA Tech-VPI.

I understand that I shall receive payment in the amount of $5 per hour plus a $50 bonus for showing a general trend of improvement in keying speed over all 40 sessions. However, I further understand 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 at $5 per hour. If for some reason the equipment used for the experiment malfunctions before the completion of the experiment, I understand that I will only be paid for the time I actually spent performing in the experiment at $5 per hour.

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. Stoudt, 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

_________________________    ______________________
Address                     Phone Number

Industrial Ergonomics Lab
ISE Department
VPI&SU
Blacksburg, VA 24061

Protocol ERGLAB 1987 Date: Jan. 1987, renewed February 12, 1989 for two
Appendix D

Derivation of $CPM_i = C + T_i B_1$
Derivation of the Log-Log function

\[ \log(CPM_i) = B_0 + B_1 \ln(T_i) \]

\[ CPM_i = e^{B_0} + B_1 \ln(T_i) \]

\[ CPM_i = e^{B_0} e^{B_1 \ln(T_i)} \]

\[ CPM_i = e^{B_0} T_i^{B_1} \]

Since \( e^{B_0} \) is constant let \( C = e^{B_0} \)

\[ CPM_i = C \cdot T_i^{B_1} \]
Appendix E

Graphs of All Time Increments and Subjects for $CPM_i = B_0 + B_1 P_i + B_2/P_i + B_3/P_i^2$ and $CPM_i = e^{B_0} P_i B_1$

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Figure E.1. Subject 1, Regression for 30 Minute Period
Figure E.2: Subject 1, Regression for 40 Minute Period

40 Minute Period

0 5 10 15 20 25 30 35 40 45 50 55

Characters per Minute

Actual

\( B^P+B_1/P+B_2/P^2 \)

\( e^{B^Trial+B_1} \)
Figure E.3: Subject 1, Regression for 50 Minute Period

Character per Minute

50 Minute Period

0 5 10 15 20 25 30 35 40 45

200 180 160 140 120 100 80 60 40 20

Actual
B^P+B1/P+B2/P^2
e^B\cdot Trial^B1
Figure E.5: Subject 1, Regression for Day Interval

- Actual
- B\text{Day} + B1/\text{Day} + B2/\text{Day}^2
- e^{B\text{Day}}B1

Characters per Minute

Day

0 5 10 15 20 25 30 35 40

0 20 60 100 140 180 220

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Figure E.6. Subject 2, Regression for 30 Minute Period
Figure E.7. Subject 2, Regression for 40 Minute Period
Figure E.9. Subject 2, Regressions for 60 Minute Interval
Figure E.11. Subject 3, Regression for 30 Minute Period
Figure E.12. Subject 3, Regression for 40 Minute Period
Figure E.14. Subject 3, Regressions for 60 Minute Interval
Figure E.15. Subject 3, Regression for Day Interval
Figure E.16. Subject 4, Regression for 30 Minute Period
Figure E.17. Subject 4, Regression for 40 Minute Period
Figure E.19. Subject 4, Regressions for 60 Minute Interval
Figure E.21. Subject 5, Regression for 30 Minute Period
Figure E.22. Subject 5, Regression for 40 Minute Period
Appendix F

Average Response Times of Each Chord by Trial
Figure F.2. Average Response Time by Trial: Chord 14
Figure F.5. Average Response Time by Trial: Chord 17
Figure F.10. Average Response Time by Trial: Chord 28
Figure F.12. Average Response Time by Trial: Chord 36
Figure F.13. Average Response Time by Trial: Chord 37
Figure F.14. Average Response Time by Trial: Chord 45
Figure F.15. Average Response Time by Trial: Chord 46
Figure F.16. Average Response Time by Trial: Chord 48
Figure F.17. Average Response Time by Trial: Chord 57
VITA

Mark Lee McMulkin was born on May 17, 1966 in Great Bend, Kansas. He received a B.S. degree in Mechanical Engineering from the University of Idaho in May 1989. While pursuing his Master Degree at Virginia Polytechnic Institute and State University (Virginia Tech), he worked as a Graduate Research Assistant for two years performing research on the Ternary Chord Keyboard and finger speed. He is a member of Tau Beta Pi and the Human Factors Society. He will be working on his Doctoral Degree in Human Factors at Virginia Tech.

Mark L. McMulkin