An Experimental Comparison of a Ternary Chord Keyboard with the QWERTY Keyboard

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(ABSTRACT)

Chord keyboards use the concept of simultaneous activation of keys to produce single characters. Some chord keyboards have been suggested as potential devices to replace the standard QWERTY keyboard which is now considered the major human-computer interface tool.

This study focused on evaluating a new chord keyboard that uses a set of eight ternary (3 state) keys. An experimental comparison of the ternary chord keyboard (TCK) with the QWERTY keyboard was conducted. Two groups of subjects were selected to participate in the study. One group was assigned to the QWERTY keyboard and the other to the TCK. The two groups learned to input a set of 17 characters. Training of each group was similar and the stimuli were identical. The study investigated how the two groups compared in attaining certain performance criteria (speed and accuracy), and how performances compared on both keyboards after fulfilling the criteria.

For each group, the number of sessions to reach the criteria was recorded along with speed and accuracy of typing. At the end of the experimental session, subjects rated some features of their respective keyboard. Performances on both keyboards were comparable in all stages with no significant differences revealed. However, executing

chords on the TCK was rated significantly more difficult than activating keys on the QWERTY keyboard.

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Introduction

In publications on the human-computer interface, it has been suggested that different data entry devices might be more efficient than the standard 'QWERTY' keyboard. Some of the alternate keyboards use the concept of chord keying. In such keyboards, concurrent activation of two or more keys is needed to produce one character.

Most of the keyboards proposed since the invention of the first typewriter keyboard have been using binary keys as their input activation elements. They have two states : on and off. Binary keys used in conventional and chord keyboards are activated by pressing down on the key tops using one finger per key.

A new concept of key activation was proposed by the VATELL Corporation, Blacksburg, Virginia, to be used along with the chording concept. A ternary (three state) key was suggested to replace the binary (two state) key. This key is activated by moving the key either forward or backward from a middle zero position (see Figure 1). Hypothesized advantages of this ternary key are the use of the (fore-aft) motion of fingers

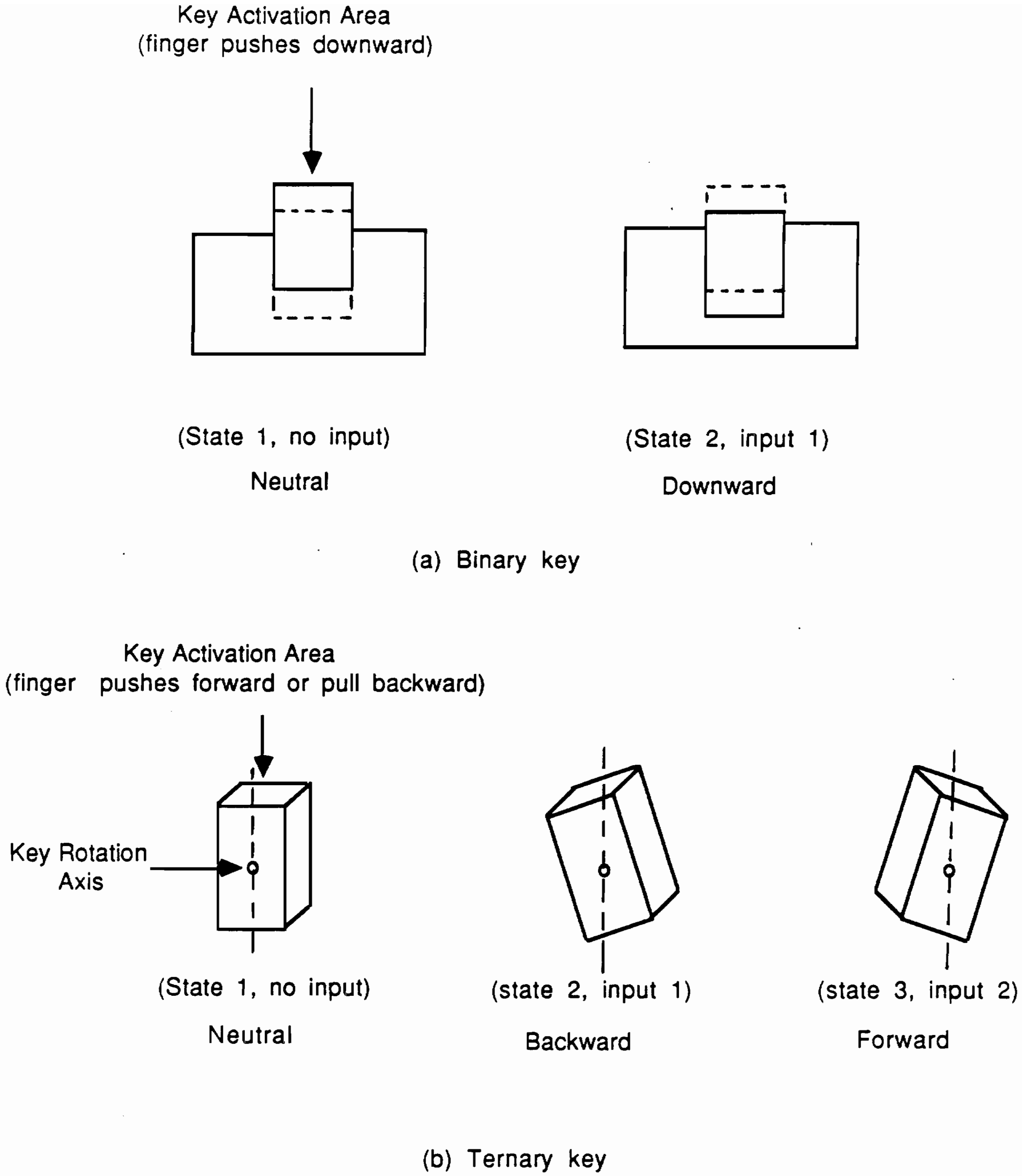


Figure 1. Binary and Ternary Keys

which may be less straining than the down-up motion; and the additional input state over the binary key.

An eight-key ternary chord keyboard (TCK), with four keys per hand was designed by VATELL Corporation (see Figure 2). Research on the proposed keyboard is in progress at the Virginia Tech Industrial Ergonomics Laboratory to explore various characteristics of the keyboard.

Some preliminary studies have been conducted on the TCK. Their main objective was to determine the trend in response times of three subjects to a randomly generated single digit stimulus over a total period of practice of about four hours. Results showed that response times were very comparable to a QWERTY keyboard. This led to the decision to conduct further and more detailed research on the TCK. The scope of future research will cover: chord coding, design configuration, and different performance analyses.

This study focused on comparing performance of subjects on the TCK, given a specific chord coding and design configuration, to that of a traditional QWERTY keyboard. To allow a valid comparison between the two keyboards, primary features of each keyboard should be considered. One of the characteristics of the TCK is that its operator has to memorize the chord patterns of all characters. This places a heavy memory requirements on the operator. In QWERTY, each character is associated with a single key as identified by the character printed on key top. The major mental requirement imposed on the beginning operator of a QWERTY keyboard is to remember the location or to execute a visual search for keys (characters) distributed across the keyboard. In touch typing, memory and retrieval requirements are considered major components of the skill. Usually, in touch typing visual search requirement is a minor component of

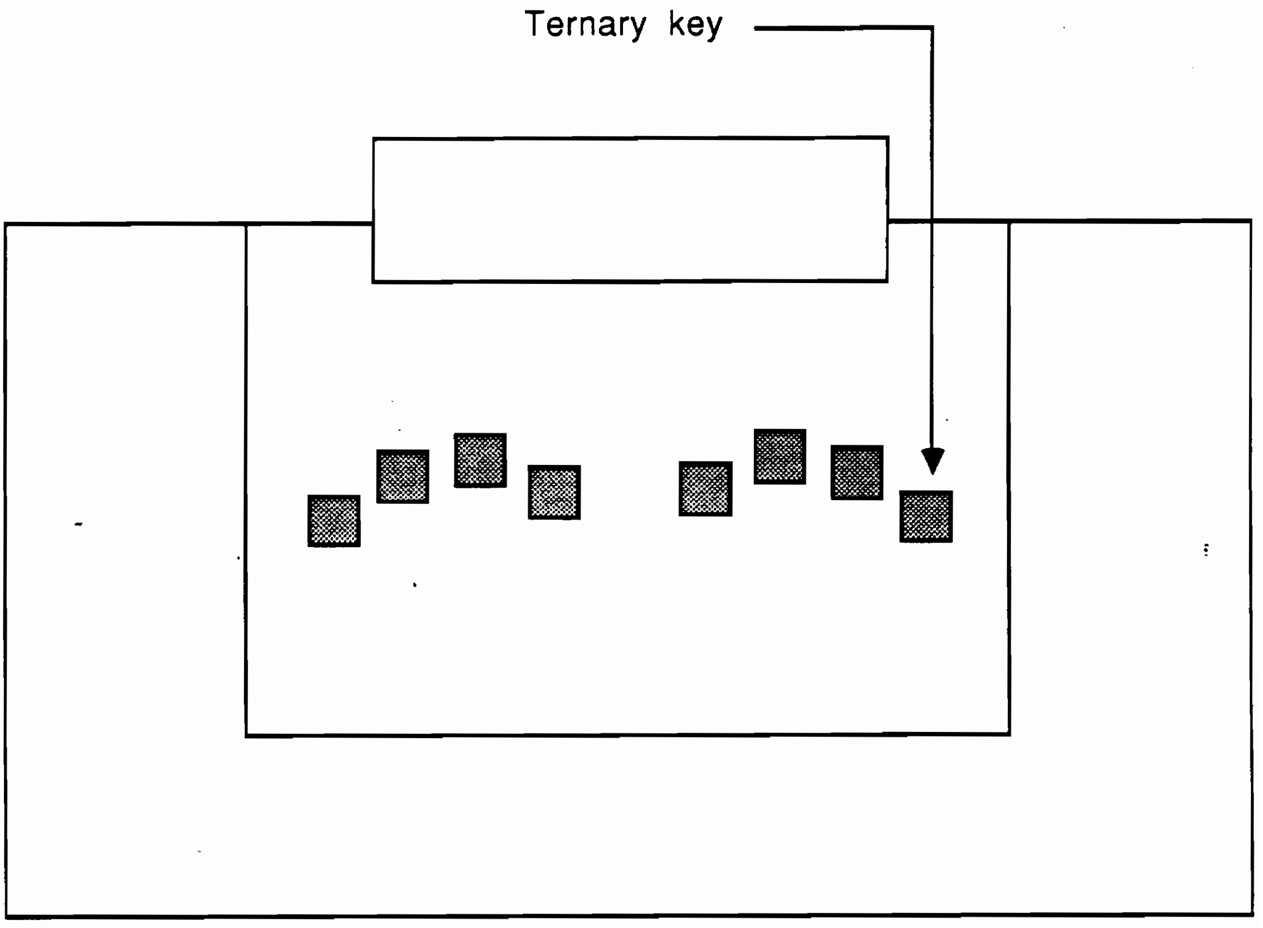


Figure 2. Ternary Chord Keyboard (TCK) (Top View). There are four ternary keys per hand, one for each finger. (The thumbs are not employed)

the skill. It is of interest to compare the components of chord typing to those of touch typing skills.

If the comparison is based on a text typing task, a total of at least 40 characters (36 alphanumerics, space, comma, period, and the shift key) is necessary. It is anticipated that long training periods are required to reach a certain performance level of touch typing and chord typing using a set of 40 or more characters. To avoid this problem, a subset of only 17 characters was suggested. This limitation in the number of characters has as its main drawback that the comparison between the two input devices is partial since only some keys of the QWERTY keyboard are used. This means that general conclusions from results about the the two devices need to be drawn with caution.

Purpose

When the TCK keyboard is considered as alternate to the standard keyboard (QWERTY), one of the main questions is: how does performance compare between the two devices provided that the operators of each device have received a similar training program ?

Two main objectives of this study (providing a set of 17 characters on each keyboard, and providing similar training for operators of each keyboard) were: (a) to discover if there is a significant difference between binary typing and ternary chord typing skills in reaching certain performance criteria, and (b) after attaining the criteria, how performances, over a specified period of time, compare on both keyboards.

Literature Review

QWERTY Keyboards

Most typewriter and computer keyboards in use today follow the original key layout designed by C. Latham Sholes for his typewriter in 1873. This key layout is often called the QWERTY keyboard in reference to the first six keys from the left of the second top row of the keyboard (Litterick, 1981). (See Figure 3). Keys were arranged so that letters that are frequently typed successively were placed as far apart as possible on the keyboard. This procedure was followed to minimize machine jamming of the type bars used at that time. That explains the apparent non-systematic arrangement of the QWERTY keyboard and the typing difficulty that faces novice typists (Norman and Fisher, 1981).

Gopher and Koenig (1983) lists the main features of a QWERTY keyboard from a human performance standpoint as follows:

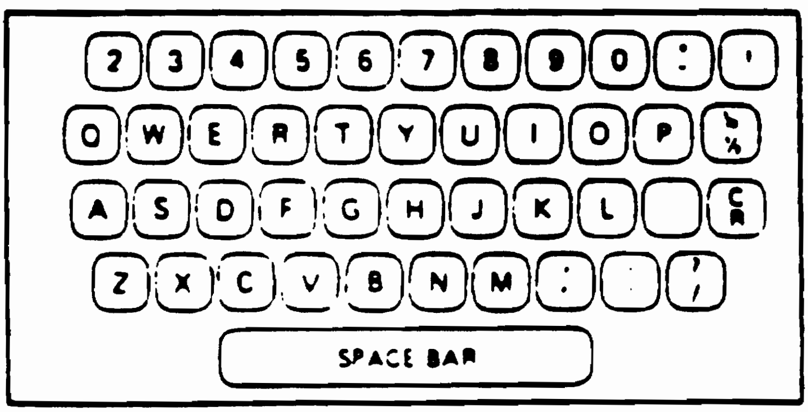


Figure 3. QWERTY Keyboard. Adapted from Pollatschek and Gilad (1984)

1. Every letter and character is entered by a separate key (although some keys may have more than one function), leading to a large size keyboard with several rows of keys,

2. each finger is responsible for several keys,

3. each hand and finger is responsible for an exclusive set of characters,

4. typing of most words requires considerable hand and fingers travel within the coordinates of the keyboard, and

5. use of a single printing head forces serial sequencing of the final outputs (i.e, printing), even when other elements (keys) allow parallel entries.

The QWERTY layout has several disadvantages and physical limitations. When touch-typing on a QWERTY keyboard, many words are typed by the left hand alone such as the words "was" and "were". That causes a higher load on the left hand (57% of typing) than on the right hand. The requirement of the typing task also loads certain fingers more than others. The distribution of typing tasks on the rows of keys in the QWERTY keyboard is not balanced. Only 32% of typing is performed on the home row of keys against 52% on the back row and 16% on the front row. Also, frequently used sequences such as "br" and "un" require excessive row hopping (Noyes, 1983a).

Biegel (cited in Noyes, 1983a) described some of the physical limitations of the QWERTY design as follows:

1. The ring and little fingers have to be stretched when moving across rows. This causes the use of finger tip which in turn causes the reduction in the stroke strength.

2. Finger travel from the home keys to other keys is difficult to conduct so that often the wrong key is struck, and

3. The division of the keys into "strips" for each finger is made by lines running obliquely from top left to bottom right across the whole keyboard. So the strips for the fingers of the right hand are at the same angle as those for the fingers of the left hand although the hands are inverse images of each other instead of congruent. (This imposes perceptual and motoric incongruities).

Despite the many anomalies inherent to the QWERTY keyboard, a few researchers have tried to defend the layout features. Kinkead (cited in Noyes, 1983a) estimated, based on the analysis of keying times, that keying speed on an "imaginary" optimal keyboard layout would not be faster than 8 % of that achieved on the QWERTY keyboard. However, Kinkead based his hypothesis on the fact that an operator can become skilled in operating any data entry device if he or she is given enough time and motivation. Thomas (cited in Noyes, 1983a) supported the idea that the QWERTY keyboard layout plays a factor in increasing the speed of typing based on the fact that the most frequent diagrams are typed by alternate hands.

QWERTY In Computers

Keyboards are and will probably be the main avenue of interface with computers for many years. Despite the criticism of the QWERTY layout, it is still used in almost all computer models with some peripheral changes around the core (the main three rows) of the layout. The QWERTY layout is a standard in the computer industry. Keyboards of computers from IBM, Apple, TRS, Commodor and other firms are nearly identical (Pollatschek and Gilad,1984).

The major difference between the computer QWERTY keyboard and the original mechanical typewriter QWERTY keyboard is in the operational characteristics of the two keyboards. In the mechanical typewriter, character printing is a simple mechanical operation. When a key is pressed down, the force applied by the finger causes the movement of a metal bar associated with that key. The shape of the character of each key is engraved on the tip of the metal bar. The engraved area of the bar comes in contact with an ink ribbon. The movement of the bar pushes the ribbon against a paper which results in the printing of the character on the paper. In a so-called electric typewriter some of the energy needed to move the masses is provided by an electrical motor. When more than one key are activated at the same time, jamming of key bars often results. In computers, keys are switches. The computer is a scanner that checks which key is activated. The keyboard also provides the "debouncing" characteristics of the keys where transient effects of key strokes are filtered out (Pollatscek and Gilad , 1984). Key strokes on a computer keyboard are identified by the position of the keys and the voltages which are converted to ASCII or other codes. The code is then translated to characters . Characters are then transformed into digitizing images which are displayed on the computer screen (Pollatschek and Gilad, 1984).

The operational characteristics of the computer keyboards make it easy to change the layout of the keyboard. Software can be used to recode the translation of key strokes into characters. Despite the ease of change, there is reluctance among computer manufacturers to consider major keyboard modification. This inertia is mainly based on economical considerations.

QWERTY Versus Modified Keyboards

Several studies focused on comparing the QWERTY keyboard with different modified keyboard layouts. Hirsch (1970) compared the typing performance of 40 novice typists on a QWERTY typewriter keyboard and on an alphabetically arranged typewriter keyboard. Results indicated that untrained subjects entered correct data faster on the QWERTY keyboard than on the alphabetical keyboard. Michaels (1971) also compared the QWERTY keyboard to an alphabetically arranged keyboard that slightly differed from the one Hirsch used in his experiment. Michaels was interested in comparing the two keyboards as a function of typing skill of subjects. Results revealed that the rate of entering correct data was greater for skilled and semi-skilled typists on the QWERTY keyboard, whereas performance was basically identical on the two keyboards for unskilled typists.

Norman and Fisher (1982) compared the performance of groups of subjects on the QWERTY keyboard to that obtained on differently arranged keyboards (horizontal alphabetic, diagonal alphabetic, and random keyboards). The researchers concluded that it was not feasible to make expert typists use the Dvorak layout, since performance on it was only about 5 % better than on the QWERTY keyboard. For novice typists, alphabetic keyboards were not found superior to the QWERTY keyboard. Norman and Fisher suggested that keyboard improvements might be achieved through major changes of the physical key configuration and not through changes made to the keyboard layout.

Chord Keyboards

The concept of chord keying dates back to the year 1942 when Achille Colombo requested a patent on a mechanical typewriter that used the chording principle, i.e., the simultaneous activation of two or more keys to produce one character. The typewriter required simultaneous pressing of one left hand and one right hand key to produce one character (Conrad and Longman, 1965). In 1950 A. Dvorak introduced a one-hand chord keyboard. No detailed information exists on this keyboard (Seibel, 1972).

Levy (cited in Noyes,1983b) presented a ten-key "binary" keyboard to be used in the Toronto Post Office. The keyboard had two banks of five keys each. Addresses were condensed into a series of characters where each character was generated by pressing the proper combination of keys. The combination of chord keying with the method of encoding addresses resulted in starting speeds higher than with manual sorting. No information was given about the chord coding of the characters (Noyes, 1983b).

Conrad (1960) introduced a letter sorting machine that required the simultaneous activation of two keys (one by each hand). Twelve keys were assigned to each hand for a total of 144 possible combinations. Performance on this keyboard was about 50 % better than the performance on a regular keyboard after 39 weeks of practice. Cornog, Hackman and Craig (1963) suggested the use of a "double binary" chord keyboard in mail sorting. On such a keyboard, there were four banks of six keys each, an arm rest bar and a panel of lights. Many other chord keyboards were proposed to be used in mail sorting such as the Burroughs and the FMC keyboards (Noyes, 1983).

Klemmer (1958) trained two subjects on a ten-key keyboard. Letters of the English language that are used most frequently were generated by depressing one key whereas other characters were generated by depressing two keys. After ten weeks of training, Klemmer concluded that learning curves were similar to the one expected on a conventional keyboard. Lockhead and Klemmer (1959) used an eight-key chord keyboard (one key per finger). The keyboard included not only the 26 letters of the alphabet (Klemmer, 1958) but also a "word-writing" mode. 100 multiple-finger patterns were assigned to whole words. They were typed by the simultaneous depression of all appropriate keys. After several experimental studies on their keyboard, Lockhead and Klemmer were optimistic about the principle of chord keying.

Most of the research on chord keyboards conducted in the 50's and 60's was targeted to specific uses such as mail sorting and court stenotypography. Technological advances in the field of computers and electronics in the past two decades geared the interest of many researchers to look into possible general-purpose chord keyboards.

Stewart (cited in Noyes, 1983b) was one of the first people to have a patent on a twelve-key "calculator like" chord keyboard (ANTEL chord keyboard). Characters are produced by pressing either single or combination of keys. Owen (1978) designed a one-hand chord keyboard, the "Writehander". In the device, eight keys are assigned to the thumb and one key to each of the four remaining fingers of the right hand. By using various combinations of the four fingers and the thumb, the Writehander can generate all 128 characters of the ASCII code. The intended use of the device is to interface with computers and other ASCII coded devices. Rochester, Bequart and sharp (1978) developed a chord keyboard for IBM that uses a new chord keying concept. The keyboard requires the use of only the thumb, index, middle, and ring fingers. Characters are obtained by the activation of various combinations of depressions called "dimples".

One of the most recent and a commercially available instrument that totally relies on the chord keying principle is the "Microwriter". This device is hand-held and has six keys (one for each finger and two for the thumb). Characters are produced by pressing different combinations of fingers (keys). The device is intended to be a portable instrument that can create a full text (cited in Noyes, 1983b).

Gopher et al. (1983,1984,1985, and 1986) have conducted extensive research on a two-hand chord keyboard. This keyboard consists of two independent five-key panels (one for each hand). Each panel (hand) can produce the whole alphabet. Research on the keyboard covered several areas, including: (a) factors involved in simultaneous data entry by using the two panels of the keyboard (b) chord coding principles and the perceptual and motor difficulties inherent in the chords, and (c) information processing and the representation of movement in long-term memory involved in chord keying.

The following is a list of general features of chord keyboards taken primarily from Gopher et al. (1983, 1984, 1985, and 1986) and from Noyes (1983b):

1. Major skill components are different from those required in standard typing. One can acquire and maintain the two typing skills side by side with little interference.

2. There are only few keys to be operated by each hand (usually four or five).

3. Each finger operates only one key.

4. No hand travel is required and no exertion of large muscles is needed.

5. Letters are identified by combination of keys, and entries are produced by typing chords. Therefore, both memory and response requirements are different from those in regular typing.

6. The comparatively small size and compactness of a chord keyboard enhances its portability and potential usability in narrow spaces such as inside a tank or aircraft.

The main argument against chord keyboards is related to the memory and retrieval requirements of these devices. Seibel (1972) argued that difficulty and complexity of chord combination have heavy memory and retrieval requirements. In addition, Seibel suggested that learning rates, response times, and number and type of errors in operating a chord keyboard are influenced by the assimilation of motor and biomechanical constraints, and hand coordination problems.

Another argument against chord keyboards is that hunt-and-peck typing is not possible on such devices and therefore they would not be suitable for novice typists (Wolstein, 1986). Wolstein also proposed that by providing a simple and straightforward chord coding and a proper operational instructions the above argument may not be true.

The positive characteristics of the chord keyboard will continue to attract the development of keyboard designs using the chord keying concept. Although most chord keyboards at the present time are targeted to specific tasks of data entry application, the advantages of such device suggest that a general purpose chord keyboard can be very competitive with the QWERTY keyboard.

Chord Coding

Coding Principles

Assignment of fingers to keys and in turn to characters (coding) is usually not a simple task in any type of data entry devices. This is especially true in chord keyboards due to the multiple number of keys needed to produce a single character. This places a heavy memory load and some special biomechanical requirements on the operator. The operator of chord keyboards has to memorize all chord combinations and their corresponding characters if there is no direct visual reference to chord combinations available on the keyboard.

Motor and perceptual elements and their interaction should be considered when attempting to reach a valid and efficient coding scheme.

There are several coding principles that have been considered in key coding. Three coding principles that have been used as general guidelines in key coding:

1. " Spatial Separation" Principle :

   This principle has been used in the QWERTY keyboard and the majority of data entry devices. Gopher and Eilam (1979) describe the skill components of this principle as follows: (a) associate each character with a separate key and with a spatial location, (b) facilitate blind positioning of appropriate locations, (c) establish structured key sequencing and five-finger coordination and control, and (d) transform long sequences or verbal symbols to strings of finger operations.

2. "Hand Symmetry" Principle :

This principle suggests symmetrical or mirror image finger(s) use of each hand in producing a character. The principle is " ... based upon a reference point. It maps letters to both hands in accordance with the anatomical structure of the performing organs. It is more closely linked with an emphasis on proprioceptive and muscle information" (Gopher et al., 1984, p. 4).

3. "Spatial Congruence" Principle :

The principle calls for the use of "congruent" finger(s) of each hand to produce a character. (For example, if the first finger of each hand is considered the first finger from the left, then the little finger of the left hand is congruent to the thumb of the right hand). This principle relies on an external objective reference point (Gopher et al., 1984).

Gopher et al. (1983, 1984, 1985, 1986) have used the above symmetry and congruence principles in their studies on a ten-key chord keyboard. Also, they combined the two principles by tilting the two panels (one panel for each hand) of the keyboard into an upright position.

Other principles had been proposed in key coding such as the use of visual imagery and pattern recognition. Those principles were the coding base of the Alpha-Dot data entry system (Sidorsky, 1974). In this system a relationship is developed between the shape of keys and the shape of printed characters under consideration. Gopher and Eilam (1979) applied a coding principle similar to the one used in the Alpha-dot to a four-key "letter-shape" chord keyboard that can produce all letters of the Hebrew language.

Chord Coding Analysis

Coding of chord combinations and the number of chords involved are essential characteristics of any chord keyboard. Assigning (perceptually and physically) easy chord patterns to the most often occurring characters of a language or another medium of application lessens the mental and physical workload on the operator of the device. This affects the speed and error rate of entering data especially over prolonged periods of operation and when a large number of chords is involved.

To understand the problem it is important to identify how chord typing is performed. Raij and Gopher (1987) give a description of chord typing. First, characters of interest are assigned to a set of chords. These are allocated to memory and retrieved in response to a stimulus. Second, the motor response is executed on the keyboard. Raij and Gopher suggested that the motor schemas of the motor response have mainly spatial representational characteristics. However, the efficiency of the movement is determined by physical and biomechanical elements.

This led Raij and Gopher to consider three main elements in chord coding : (a) motor difficulty of each chord, (b) relative perceptual difficulty of each chord, and (c) the influence of motor and perceptual determinants on actual data entry. To address these topics, Raij and Gopher conducted experimental work to develop two separate indexes that assess the influence of motor and perceptual factors in chord keying. The results revealed that perceptual and motor factors equally but independently affected the efficiency of data entry. Another finding of the study was that the efficiency of finger movements does not depend only on the physical and biomechanical constraints, but also on the perceptual factors of the chord. As a conclusion, Raij and Gopher stated that for a thorough understanding of chord complexity (motor and perceptual), an individual analysis of each chord is a necessity.

Similar experimental approaches should be considered in determining the perceptual and motor difficulties of different chord combinations on the TCK. The specific issues to be addressed are the independence of motor and perceptual measures and their relative contribution to ternary chord typing. A comparison between the results obtained by Raij and Gopher (1987) and the expected results on the TCK would be of future interest.

Lockhead and Klemmer (1959) were the first to use information theory in chord coding (applied to their eight-key chord keyboard). For each chord pattern, all patterns using the same number of fingers as that chord pattern were counted. This number was converted to an information measure by taking the logarithm to the base two. One was added to this value for each pattern to eliminate zeros and each was multiplied by: (a) The total number of keys involved in the total pattern, and (b) 0.8 if the involved keys were adjacent on one hand and 0.6 if they were adjacent on both hands, and (c) 0.6 if the pattern was bilaterally symmetrical and 0.9 if it was unilaterally symmetrical. The resulting values were rank-ordered with the lowest number considered the easiest pattern. The easiest patterns were then assigned to the most frequent words of the English language (Lockhead and Klemmer, 1959). No details were given about the determination of the four multipliers mentioned above.

A similar chord coding strategy can be followed in coding the TCK chord patterns. A research strategy should be developed to determine the magnitudes and validity of the multipliers that will be used, important issues which Lockhead and Klemmer did not address.

Ratz and Ritchie (1961) suggested that chords can be ranked according to chord typing reaction times by subject in response to visual a stimulus representing the chords. The ranking is an indication of the relative perceptual difficulty between chords. Easy chords can be assigned to the most frequently used letters or words. This approach can also be applied to future TCK research.

Although chord coding is not a primary focus of this study, the obtained results will be useful in analyzing the coding used (specified later). The results of this study gave an indication of the relative difficulty between the chords. This is a major issue that has a great impact on the characteristics of the TCK.

Chord Keyboards Versus Other Keyboards

In research concerning chord keyboards, very few studies have been devoted to comparing performance levels between a proposed keyboard and existing keyboards, such as the QWERTY keyboard, under similar training conditions. Conrad and Longman (1965) were the first to attempt such a comparison in an extensive manner. The main objective of their study was to compare the performance of two groups of subjects, one group on a standard typewriter (QWERTY) and the other on a chord keyboard, after receiving identical training programs.

Conrad and Longman pointed out some of the methodological elements that should be considered when comparing performances on two devices. Those elements include: (a) subjects should be drawn from a population with homogeneous relevant qualities, (b) the training program given to the different groups should include identical material, (c) the experimenter should be the same for all groups to avoid experimenter effects between groups, (d) a detailed description of practice material should be given, and (e) practice should continue to a point where comparison can reasonably be made.

In this study the above methodologyical guidelines were considered to assure valid comparisons between the two keyboards.

Results found by Conrad and Longman indicated that improvement rates over a 3 1/2 hours daily, 5 days a week for 7 weeks training period were similar on both keyboards. Performance rate was not used as a comparison criterion since the training period did not exceed one year, a period that was estimated to result in "terminal performance" levels. Also, they found that the learning period on the chord keyboard was shorter than on the standard typewriter. This is considered advantageous in situations where operators of data entry devices are hired to be trained (Conrad and Longman, 1965).

Wolstein (1986) compared performance on two data entry devices that used the chord keying concept. The devices were the Microwriter (described earlier) and the "4x4" keypad, a calculator-like chord keyboard. The main objectives of Wolstein study were: (a) to determine which device gives the best performance with limited amounts of training and practice, (b) to determine whether the use of mnemonics on the Microwriter results in less errors or whether the absence of mnemonics results in confusion among chord patterns, and (c) to determine the time it takes to reach a criterion level of performance on both keyboards.

Wolstein concluded that handprint-type chord keyboards should not be used unless long training periods are given to their operators. Wolstein also suggested that changes in the coding scheme used in the devices might affect the outcomes of the results.

Gopher and Raij (1986) conducted some comparative experiments between their two-handed ten-key chord keyboard and the QWERTY keyboard. They found that performance of subjects on the chord keyboard were superior to the performance of the group of subjects on the standard (QWERTY) keyboard given that training periods were identical on both keyboards. Subjects reached entry rates of 30-35 words per minute after only 20 hours of practice on the chord keyboard and 20-25 words/min on the QWERTY keyboard for the same practice period. After 40 hours of practice, some subjects were approaching an entry rate of 60 words/min on the chord keyboard. Error rates were low and showed a constant decrease with practice on the chord keyboard. Another important conclusion of Gopher and Raij is that the skills needed for chord typing and touch typing on a QWERTY keyboard are different. This suggests that components of chord typing skills are different from those of typing on a QWERTY keyboard. This finding implies that an experienced typist on a QWERTY keyboard can add the chord typing skill with no major interference from his or her touch typing skill.

Richardson et al. (1987) evaluated keying performances on three types of keyboards: (a) a one-hand conventional calculator keyboard, (b) a two-hand 10-key serial keyboard, and (c) a two-hand 10-key chord keyboard. Subjects were trained on each keyboard until they reached predetermined performance level criteria (speed and accuracy of typing). Practice sessions consisted of encoding five-digit strings. Fewer sessions were needed to reach the performance criterion on the calculator and serial keyboard than on the chord keyboard. Mean training time required to reach the performance criteria (875 msec per string, 95 % accuracy) of encoding two-digit was about 22 hours on the calculator and the serial keyboard and 97 hours on the chord keyboard.

For acquiring similar typing requirements, i.e., encoding two-digit and five-digit strings, Gopher (1986) suggested that on the 10-key chord keyboard (Gopher,1983) similar performance levels to the one stated by Richardson et al. (1987) can be reached with a short training period. The contradiction of results can be attributed to several factors. First, the design characteristics of the two chord keyboards are different, which may affect data entry efficiency. Second, chord coding influences response time on a chord keyboard. Inefficient chord coding of a chord keyboard can result in increased response times. Third, the strategy followed in making subjects commit the chord patterns to long-term memory can affect the period of training required to reach a certain performance level.

Literature Summary

Almost all computers use the QWERTY keyboard as their main interface tool. It is apparent, from the literature cited above, that this tool does not provide an efficient interface between computers and their users, especially novice users. Many researchers supported the idea of looking into alternate interface devices that can deliver the same or similar functions of those of a QWERTY keyboard, but with higher efficiency and ease of use. In several cases, chord keyboards have demonstrated to have high potential to compete with the QWERTY keyboard. When considering a certain chord keyboard, keyboard design characteristics and the chord coding strategy adopted are the two main factors affecting its efficiency.

Experimental Hypothesis

This study was designed to explore two major hypotheses. The first one was: the number of practice sessions needed for a novice TCK user to reach certain performance criteria is identical to that of a QWERTY novice user. The second hypothesis was: over a specified period of time, performance levels of QWERTY user, of similar typing proficiency, are identical. Note that the study was conducted under several experimental constraints that will be discussed later.

Method

Subjects

Eight subjects, four male and four female, participated in this study, and were compensated for their time. They were college students between the ages of 18 and 25 years (mean age 20 years). All participants were required to be native speakers of English, in order to eliminate letter or word recognition difficulty and to avoid language interference. In addition, all subjects were required to be novice typists and novice in using any musical instrument that requires multiple key-entry such as piano, guitar, or saxophone. (The selection of subjects was based on a screening procedure that is discussed later in the experimental procedure section of this document).

Experimental Apparatus

Ternary Chord Keyboard (TCK)

The ternary chord keyboard (TCK) used was depicted earlier in Figure 2. Activation of a key on the TCK is detected by two microswitches, one in the front side and one in the back side of the lower part of the key. The microswitches (16 for 8 keys) are connected to a digital termination panel which is mounted on the keyboard. The panel is connected to an Input/Output carrier card on an IBM (AT) computer via a bus cable. A software program was specially developed to recognize and manipulate inputs from the TCK.

Chord Coding The TCK

The 8-key TCK is capable to produce 6560 (three to the power eight) possible combinations. However, if only one finger from each hand is simultaneously used to produce a character, a subset of 64 combinations exist (four fingers per hand and two active states per key).

In this study, valid input to the TCK was limited to a set of 17 characters. The set includes 15 letters, a space, and a help command. This limitation was selected to avoid long training periods that would have resulted if a large set of characters was involved, and to allow an experimental comparison within a fairly short period of time.

Regarding the assignment of chords to characters (coding), three principal guidelines were used. First, the principle of symmetry between the left and right hand was applied. It calls for the use of the same finger of each hand to obtain a chord. Second, finger strength and tapping rate were considered in chord coding. Alden et al. (1972) reported that for both hands, excluding the thumb, the index finger has the highest finger-pushing force followed by the middle, the ring, and the little fingers. Finger-tapping rate follows the same decreasing order. It was hypothesized that assigning the most frequently occurring letters to pairs of fingers that have high tapping-rate and high pushing-force would facilitate the performance on the TCK. Third, results from preliminary studies on the TCK favored unidirectional motions of pair of fingers. Response times and error rates per character were lower for chords that were produced using unidirectional motion of pair of fingers.

Table 1 gives a list of the 17 characters that were used in the TCK part of the study and their corresponding chord coding by fingers. The 15 letters were ordered according to their frequency of occurrence in the English language, with the letter "E" being the most frequent letter (Konheim, 1981).

The QWERTY Keyboard. Adapted from Pollatschek and Gilad (1984)

The QWERTY keyboard was an IBM (AT) keyboard with the exception that the keys were not labeled ("blank keys").(See Figure 4) The 17 characters listed earlier were used also in the QWERTY keyboard as the only valid characters. The spatial locations of the 15 letters and the space were not changed from their original keyboard layout locations. The help mode key was assigned to the "Tab" key which was also blank.

Table 1. Chord-Coding by Fingers of the 17 Characters

	LEFT HAND					RIGHT HAND			
Character	L	R	M	I		I	M	R	L
E				F		F			
T			F				F		
A			A				A		
O		F						F	
N		A						A	
R	F								F
I	A								A
S				F		A			
H				A		F			
D			F				A		
L			A				F		
C		F						A	
F		A						F	
M	F	A						F	A
U	A								F
SPACE				A		A			
HELP			F	F		F	F		

L= LITTLE FINGER
R= RING FINGER
M= MIDDLE FINGER
I= INDEX FINGER
F= FORE
A= AFT

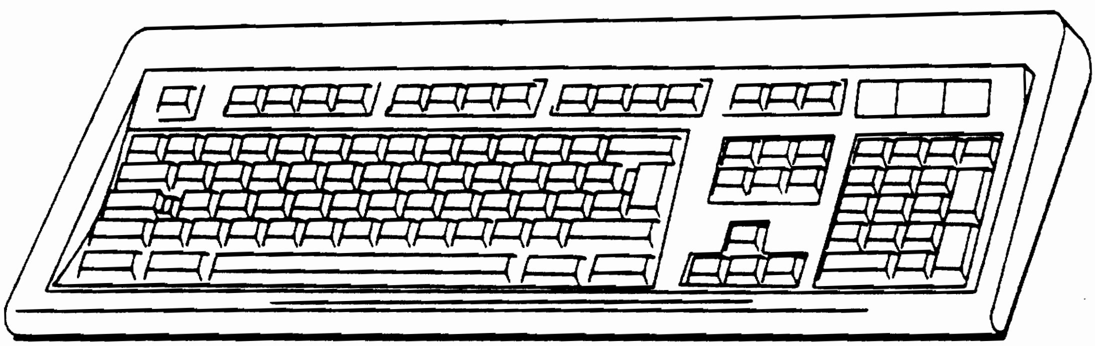


Figure 4. The Blank-Key QWERTY Keyboard. Adapted from IBM Corporation (1986)

Experimental Design

The subject activities were recorded in four stages : practice stage, training stage, testing stage, and subjective ratings stage. In the first three stages, typing performance data were obtained. In the fourth stage, responses to a series of bipolar subjective rating scales were recorded.

Practice Stage

This was the first stage in which the subjects participated. The stage was designed to familiarize subjects with the functions of each keyboard. The experimental design was "one factor within-subject". It is shown in Figure 5. The design involves one independent variable; letter.

The indedependent variable, Letter, was a fixed-effects, within-subject variable. As shown in Figure 5, there were 15 levels (letters) considered: E, T, A, O, N, R, I, S, H, D, L, C, F, M, and U. Data were collected from the last session of the practice stage of those subjects who were assigned only to the TCK to allow a comparison between chords.

	Subject			
Letter	1	2	3	4
E				
T				
A				
O				
N				
R				
I				
S				
H				
D				
L				
C				
F				
M				
U				

Figure 5. Practice Stage Experimental Design. One Factor Within-Subject Design

Training Stage

For this stage, the experimental design was "one factor between-subjects". The independent variable, keyboard type, was a fixed-effects variable with two levels: TCK and QWERTY. The design is shown in Figure 6.

Testing Stage

The experimental design was "2x5 mixed-factor". The design matrix appears in Figure 7. This design involves two independent variables: keyboard type and session block. Keyboard type was a fixed-effects, between-subjects variable with two levels investigated: QWERTY and TCK. Session block was a fixed-effects, within-subject variable. The variable had five levels: session-block 1, 2, 3, 4, and 5.

Subjective Rating Stage

The experimental design for this stage was a set of seven "one factor between-subjects" designs. Each design (one for each rating scale) involved one dependent variable, keyboard type. ~~Again,~~ Keyboard type was a fixed-effects, between-subjects variable. The two levels investigated were: TCK and QWERTY. (See Figure 8).

In all stages discussed above, subjects were considered as a random-effects variable.

Keyboard Type	
QWERTY	TCK
S: 1,2,3,4	S: 5,6,7,8

Figure 6. Training Stage Experimental Design Matrix Design. One Factor Between-Subject Design

	Keyboard Type	
Session-Block	QWERTY	TCK
1	s : 1,2,3,4	s: 5,6,7,8
2	s : 1,2,3,4	s: 5,6,7,8
3	s : 1,2,3,4	s: 5,6,7,8
4	s : 1,2,3,4	s: 5,6,7,8
5	s : 1,2,3,4	s: 5,6,7,8

Figure 7. Testing Stage Experimental Design Matrix. 2x5 Mixed-Factor Design

Keyboard Type	
QWERTY	TCK
S: 1,2,3,4	S: 5,6,7,8

Figure 8. Subjective Rating Stage Experimental Design Matrix Design. One Factor Between-Subjects Design (Same Design for each Scale)

Dependent Variables

In order to make comparisons between the two keyboards under consideration, two types of data were collected from each subject, objective and subjective data.

Objective measures were collected and used to determine and observe the typing performance of each subject and between the two groups of subjects. Those measures were collected during the first three stages of the experiment (practice, training, and testing stages). For the practice stage, the two dependent measures that were collected from each subject were: mean time per character per practice session (MTP) in msec per character and mean percent accuracy per character per practice session (MAP) in percent. For the training stage three dependent measures were collected : mean time per character per training session (MTT), mean percent accuracy per character per training session (MAT), and number of training sessions to reach the performance criteria. For the testing stage, two dependent variables were considered: mean time per character per session-block (MTB) and mean percent accuracy per session-block (MAB).

In addition to performance measures, subjective assessment of different features of each keyboard was gathered from each subject. Subjects responded to a set of seven bipolar scales corresponding to their respective keyboard. The seven bipolar scales of each keyboard and the accompanying instructions (Grenell, 1988) are presented in Appendix A. Since features of the two keyboards used are different in many aspects, it was difficult to develop rating scales that addressed exactly the same issues. However, the scale questions and their bipolar adjectives were developed to be as matched as possible. For example, scales 1, 6, and 7 of each set of scales (TCK and QWERTY) were the only scales that differed in their question wording and yet they were addressing almost the same issues (see Appendix A). That was done to make questions and scales compatible with their respective keyboards. Note that the rest of the scales were identical.

Experimental Procedure

Subject Screening

Everyone has at least seen and has a general idea about the use of a QWERTY keyboard and pushed a binary key similar to the one used in keyboards : calculators, ovens, door bells, etc. Keying and keyboard concepts are part of modern civilization. However, the concepts of ternary keying and chord keying are new to most people. This made the selection of true novice typists on a QWERTY keyboard a very difficult task especially among college students. Hence, subjects were selected to be as inexperienced as possible with the keyboard. The selection criteria were based on a screening procedure discussed below.

All potential subjects were first given an informed consent form to read. The form is presented in Appendix B. After consenting to participate in the screening procedure, they were given a written instructions form to read (see Appendix C). The experimenter then demonstrated the features of the keyboard and the task requirements. Each potential subject was given an eight-line Tinker passage to type using the computer keyboard and screen (see Appendix D). The experimenter observed the typing behavior of the subject and recorded information regarding that behavior. See Appendix E for a list of information recorded.

A subject was considered suitable to participate in the experiment based on the following criteria:

1. Usage of computer/typewriter should be less than two hours per week.

2. "Hunt and peck" typing used.

3. Subject uses no more than two fingers per hand.

4. Eyes kept on keys (should look for keys).

5. Fingers are not on the home row.

6. The gross net words per minute (GNWP) is less than 30.

7. Subject is, at best, novice in using any musical instrument that requires multiple key entry.

The GNWP criterion was based on information received from a typing instructor who said that any person who hunts and pecks is considered a novice typist and that a 30 GNWP is considered a fairly low speed of typing (indicative of hunt and peck). The musical instruments constraint was included to avoid possible interference between musical notes execution on musical instruments requiring multiple key entry (chords) and chord execution on the TCK. Subjects were questioned with regard to their experience with musical instruments, but no related testing was conducted.

Qualified subjects were randomly assigned to be tested on either the TCK or the QWERTY keyboard.

Testing On The QWERTY Keyboard

At the beginning of the experiment each subject was given an informed consent form to read (see Appendix F). If the subjects consented to participate in the experiment they were given one page of general instructions describing the task and its requirements (see Appendix G).

Practice Stage

The subject first read instructions describing, in general terms, the task requirements of this stage (see Appendix G). As stated earlier, all keys on the computer QWERTY keyboard were blank. This required the subjects to memorize the spatial location of each key of the 17 characters set.

The experimenter first demonstrated the function of the help key (the original "Tab" key). Two to three minutes were given to subjects to familiarize themselves with location and operation of the help mode key.

Practice in the location of the remaining 15 characters began according to a part-task training paradigm : the 15 letters were randomly divided into three groups of five letters each. The subject was introduced to one letter-group at a time in the order listed in Table 2. Starting with letter-group 1, the subject was presented with a card showing a

Table 2. List of Letter-Group Used in the Practice Stage

Group	Letters
1	D,T,R,N,U
2	I,L,O,S,A
3	M,C,E,F,H

drawing of the keyboard layout with the location of all five keys in the letter-group (see Figure 9 for an example) . The subject had a five-minute period to become familiar with the key-letter relation. After the five-minute period, the card was taken away and the subject was ready to use the keyboard.

The subject tried to type one letter at a time. The letter was randomly drawn by the computer from the letter group under consideration and displayed in the middle of the screen.

For each letter group, a session consisted of 200 randomly displayed letters : this is referred to as ″practice session″. During each session, the Help mode was accessible. Whenever the subject pressed the Help key, a window was displayed in the lower part of the screen. The window showed a graphical representation of the keyboard layout, with only the key of the letter that the subject was trying to type highlighted. For each letter group, the subject participated in four consecutive practice sessions with five-minute break between each session. During the break, the subject was allowed to examine the letter-group key-location card, if needed. The subject was called on, after a passage of at least four hours, to participate in the next letter group practice session.

After finishing the last session of letter group 3, the next four practice sessions contained all 15 letters (200 randomly displayed letters each) with a five-minute break between the two sessions. No key-location card was provided before each of the four sessions, but the Help key was available. At the end of the fourth session, the practice stage was considered terminated.

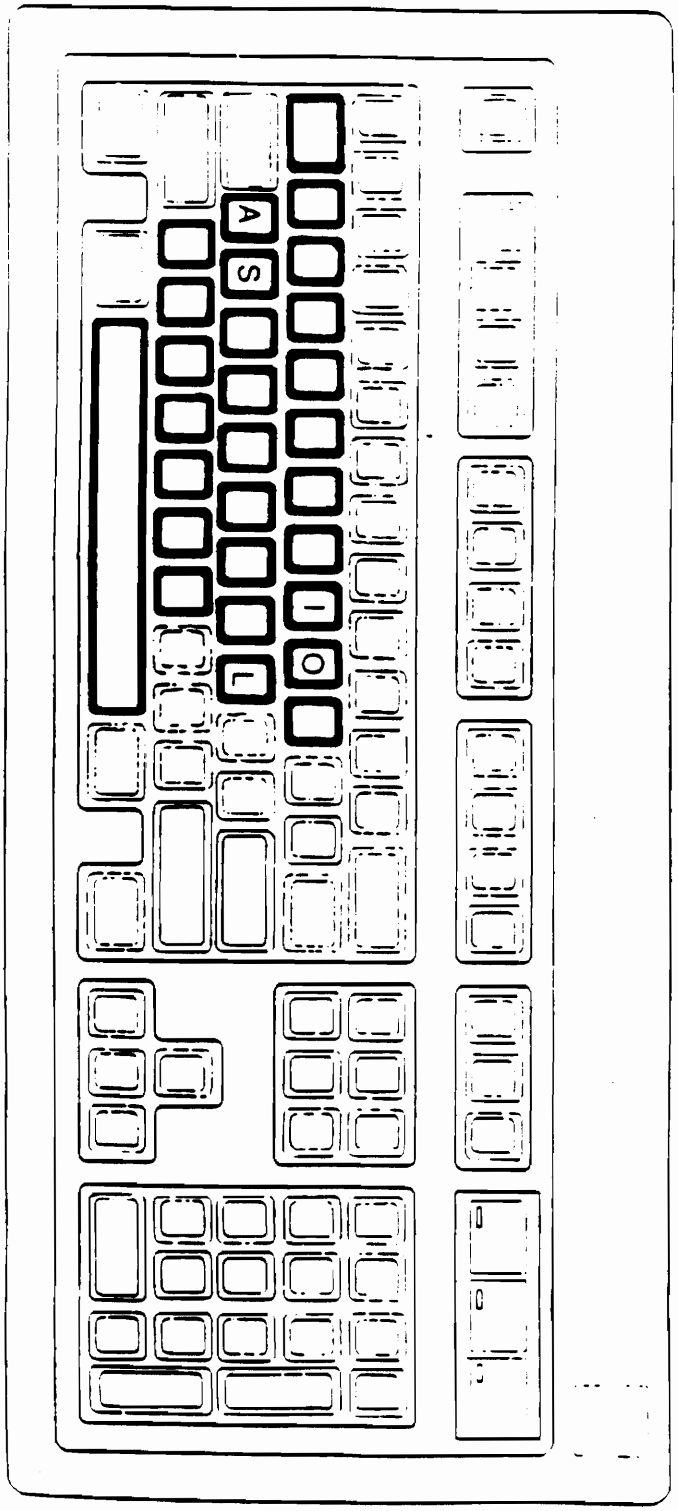


Figure 9. Letter-Group Key-Location Card for the Letters I, O, A, S, and L. Adapted from IBM Corporation (1986)

Training Stage

At the beginning of this stage subjects were given general instructions to read describing the task materials and requirements for this and the following stage of the experiment (see Appendix G). The experimenter introduced the function and location of the space bar. At this stage the subject typed a total of 27 lines of text, one line at a time. This is referred to as a "training session". The text consisted of a collection of English words that are combinations of only the predetermined 15 letters. All letters were capital letters. No commas, periods, or any other characters were included in the text. It was important to assure that every text content of each session provided the same level of difficulty and provided a similar frequency of occurrence of letters. To do so, all sessions of this and the next stage were created by randomly selecting the 27 lines of each session from a large text file (3500 lines). The selection was made one line a time, with replacement.

A 5-second countdown preceded each session. At the beginning of each training session the screen showed two lines of text : the line which the subject had to type, and the following line. After the subject finished typing the first line of the text, the screen showed a total of four lines of text. Starting from the top, the four lines were: the line that the subject had already typed, the line which the subject was trying to type, the line the subject was typing, and the following line (see Figure 10). A cursor was placed under the letter the subject is trying to type. The letter had to be input correctly before the subject could proceed. A beep signaled the entry of an incorrect character. If the incorrectly entered character was one of the valid 16 characters, it was displayed in the same position of the character that had to be typed, otherwise, a question mark (?) would be displayed.

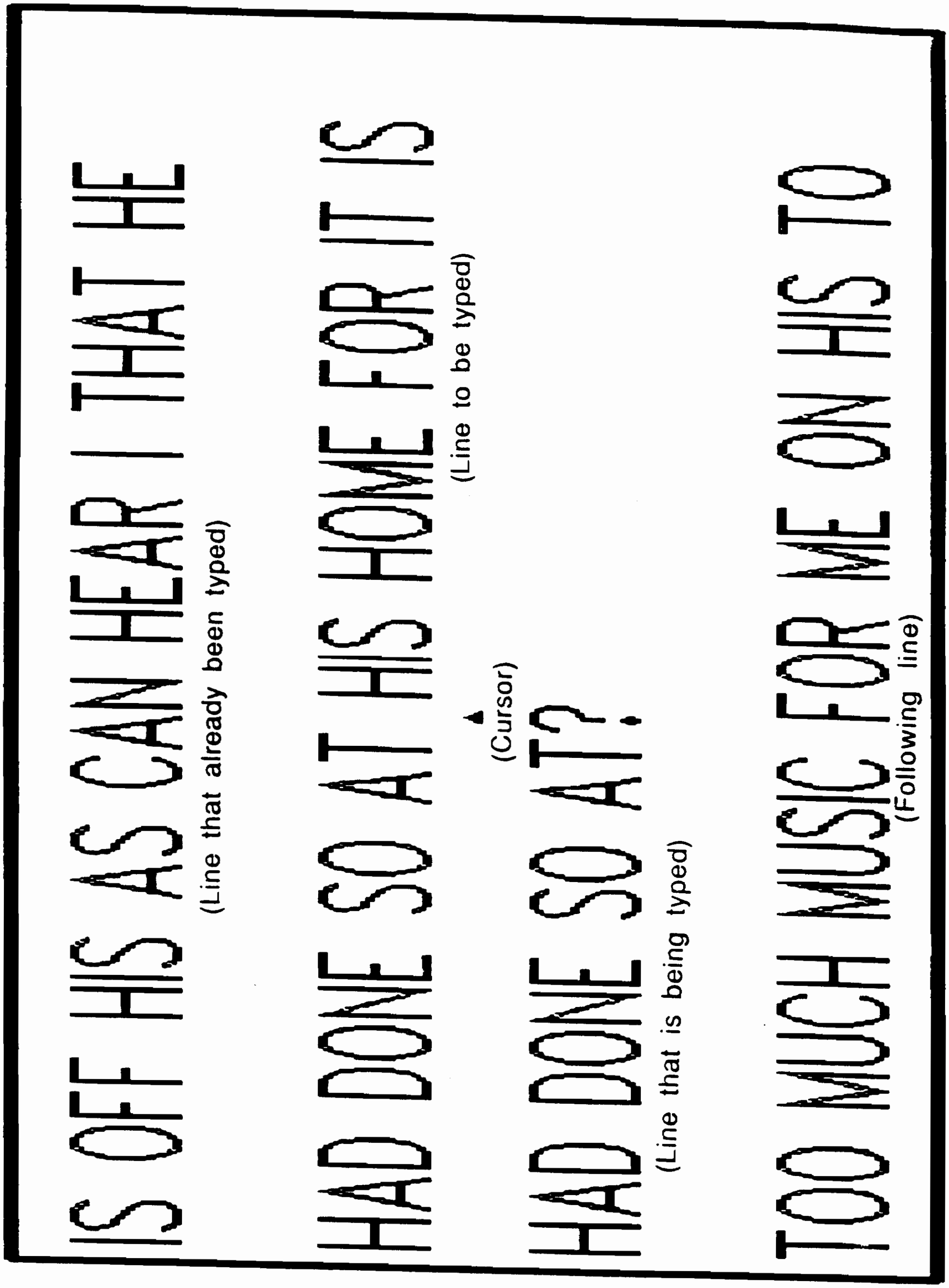


Figure 10. Sample of a Training Session Screen

The subject was able to access the Help window at any time during the session by pressing the Help key. The window was overlayed on top of the bottom line of the screen. The help window was identical to the one described earlier in the learning stage, but included all 16 valid characters.

A space separated each single word in each line. The correct typing of the last letter in each line-to-match automatically caused the scrolling of the screen (the typed line moves to the top, the bottom line-to-come becomes the line-to-type, and a new line-to-come appears on the screen). No space was required at the end of each typed line and the subject was able to type words (letters) from the line-to-come during the scrolling of the screen (there was a 1 second lag time due to scrolling).

Each session was separated by a five-minute break. A total of four training sessions was given each day. Training sessions continued until the subject met the following concurrent performance criteria: a) 97% mean percent accuracy per character per training session, and b) 800 msec/character mean time per character per training session. This marked the end of the training stage.

Testing Stage

After satisfying the performance criteria, the subject participated in 20 additional sessions (4 sessions per day) identical to those described in the training stage but called "testing sessions". Four testing sessions each were combined into one "session block". Subjects participated in one session block per day. Subjects were not told about change from the training stage to the testing stage. No feedbacks were given to subjects about their performance progress or levels to avoid possible undesired motivational effects based on performance aspiration.

The end of the 20th testing session marked the end of the testing stage for subjects who were assigned to the QWERTY keyboard .

Subjective Rating Stage

At this stage subjects read the instructions for the subjective rating scales described earlier and responded to the seven bipolar scales (see Appendix A). Subjects were then debriefed about the purpose of the study, thanked for their participation, and compensated for their time.

Testing On The TCK

The experimental procedure for the TCK was identical to the one described above for the QWERTY keyboard with the following exceptions: (a) instead of key-location cards, chord-pattern cards were used with each pattern representing a specific character (see Figure 11 for an example); and (b) during all sessions, the help window depicted the chord pattern of the character under consideration.

Text material presented to subjects in both groups was identical.

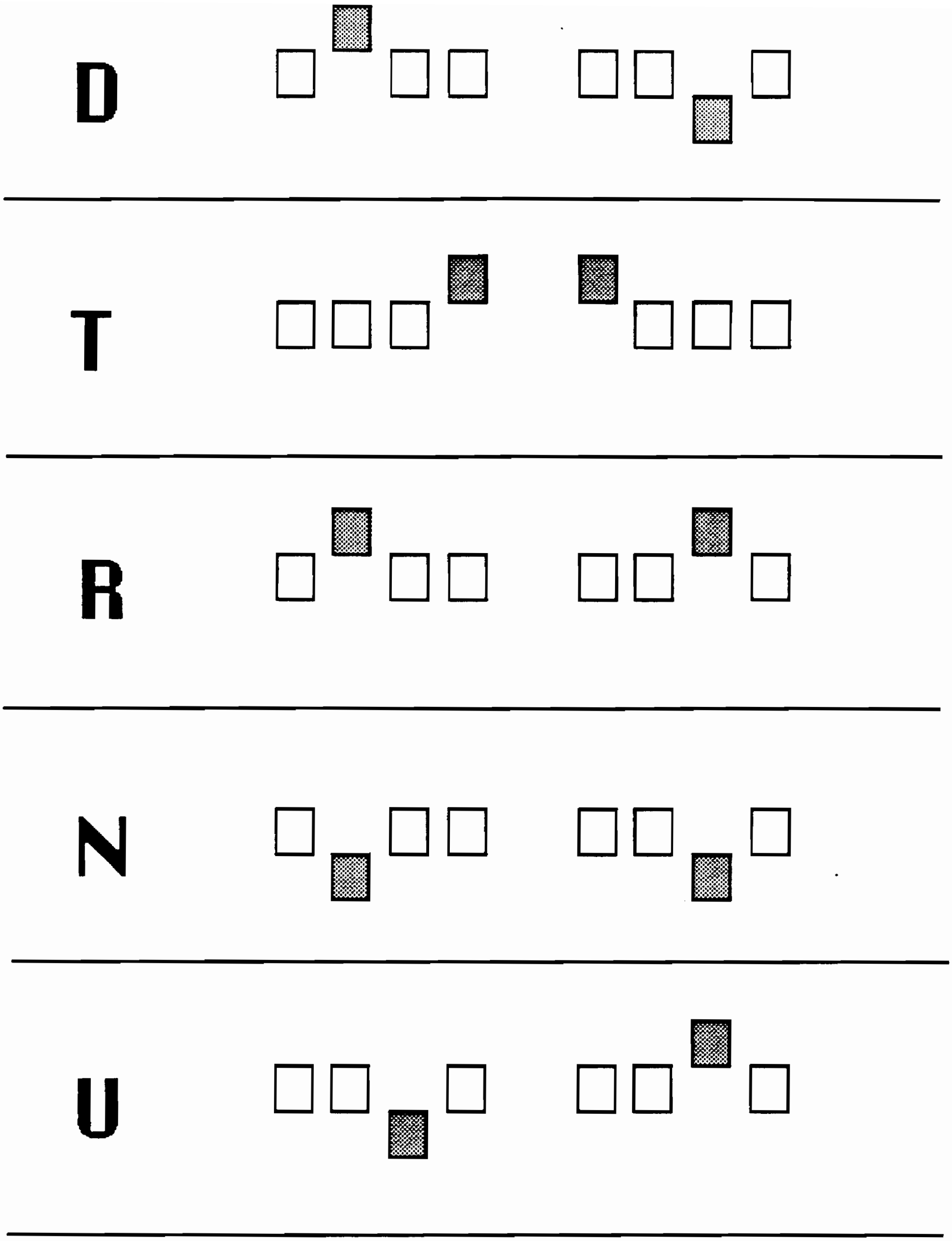


Figure 11. Sample of a Letter-Group Chord-Pattern Card

Data Analysis and Results

Data analysis procedures were performed separately for the four separate sections: a) practice stage, b) training stage, c) testing stage, and d) subjective rating stage sections. The first three sections dealt with assessing the typing task performance. The fourth section dealt with assessing the subjective rating.

Practice Stage

The main objective of analyzing data collected from this stage was to observe any significant difference in the 15 chord assignments of the 15 letters used in the experiment. The dependent variables, as mentioned earlier, were Mean Time per letter per Practice stage (MTP) and Mean percent Accuracy per letter per Practice stage (MAP). Data were collected only for the last practice session of the combined 15 letters for the TCK group. The task was to respond to a single letter stimulus drawn randomly out of the

15 letters set and displayed in the middle of the screen. There was a total of 200 randomly displayed letters.

After the end of the first practice session of the combined 15 letters, all subjects in both groups never referred to the available help mode till the end of their participation.

Since the task involved two dependent variables, MTP and MAP, a multivariate analysis of variance (MANOVA) procedure was appropriate.

Multivariate Analysis of Variance

The design was "one factor within-subject" with letter as a fixed-effects, within-subject variable that involved 15 levels. The Wilk's U statistic was computed for the main effect, letter, and converted to the familiar F statistic. The MANOVA summary table is shown in Table 3. Letter effect was not significant, $F(14,42) = 1.13$, $p = 0.3313$. A plot of letter versus MTP and MAP for all subjects of the TCK group is presented in Appendix H.

Training Stage

As described before, subjects participated in several training sessions that had typing text stimuli presented on the computer screen. The main objective of the analysis of this section was to discover whether the two keyboards differed in attaining the pre-set performance criteria. Again, the criteria were: 97 % mean percent accuracy per character per training session (97% MAT) and 800 msec mean time per character per training

Table 3. Practice Stage MANOVA Summary Table

Source	dv	df(H)	df(E)	U	F	P
Between-Subjects						
Subject (S)	2	---	---	---	---	---
Within-Subject						
Letter (L)	2	14	42	0.5216	1.13	0.3313
L*S			(Error Term for L)			

where: dv = number of dependent measures
df(H) = degrees of freedom for treatment effect
df(E) = degrees of freedom for error effect

U = Wilk's likehood ratio statistic

$$\frac{|E|}{|E+H|},$$ where :

| E | = determinant of sum of square and cross-products for error

| E + H | = determinant of the sum of squares and cross-products matrix for error, and sum of squares and cross-products matrix for treatment

session (800 MTT). The independent variable, keyboard type, was a fixed-effects, between-subjects variable with two levels: QWERTY and TCK. The dependent variable was number of training sessions to criteria.

Since the data gathered cannot be considered being on an interval scale, the analysis employed only nonparametric statistical tests. Siegel (1956) suggested, for the case of two independent samples of equal size, the Kolmogorov-Smirnov test as best suited if one deals with ordinal data but cannot make the assumption of continuity. As shown in Table 4, results indicate that the two groups did not statistically differ in the number of training sessions to criteria ($p > 0.01$).

The number of training sessions that each subject of each group took to reach the criteria is presented in Appendix I. The MAT and MTT for the two groups are presented in Appendix J.

Testing Stage

After reaching the performance criteria, subjects participated in five experimental sessions (session blocks), one session per day. (Each session block consisted of four testing sessions that were separated by five-minute breaks). The main objective of the analysis of this stage was to explore any significant difference in the typing performance of the two groups of subjects over 5 days. All subjects were at the same level of typing performance at the beginning of this stage.

Table 4. Kolmogorov-Smirnov 2-Sample Test on Number of Training Sessions to Criteria

N1,N2	K_D	P
4	1	> 0.01

Where K_D is the largest difference between the two cumulative distributions; N1 = N2 = 4

Multivariate Analysis of Variance

Since there were two dependent variables that described the typing performance at this stage, mean time per character per session-block (MTB) and mean percent accuracy per character per session-block (MAB), a multivariate analysis of variance was an appropriate analysis approach. Again, session block was a fixed-effects, within-subject variable with five levels and keyboard type is a fixed-effects, between-subjects variable with two levels.

Table 5 gives a complete MANOVA summary table. As shown in the table, session block was the only effect revealed to be significant, $F(4,24) = 46.34$, $p = 0.001$. This finding was expected due to the training effect inherent within each session block.

Two separate analysis of variance (ANOVA) procedures were conducted, using MAB and MTB as dependent measures respectively, to detect which of the two measures contributed to the "session block" significant effect. Tables 6 and 7 are complete ANOVA summary tables for the MAB and the MTB respectively. The only significant effect revealed was session block, $F(4,24) = 45.77$, $p = 0.0001$ when using MTB as dependent measure (Table 7). Figure 12 is a plot of MTB and MAB for each session block over all subjects of each keyboard. Figures 13 and 14, 15, and 16 give the MTB and the MAB of each session block for each subject in the TCK group and the QWERTY group respectively.

Table 5. Testing Stage MANOVA Summary Table

Source	dυ	df(H)	df(E)	U	F	P
Between-Subjects						
Keyboard (KB)	2	1	6	0.5886	1.75	0.2569
Subject (S)/KB				(Error Term for KB)		
Within-Subject						
Session-Block (BL)	2	4	24	0.1087	46.34	0.0001 *
BL x KB	2	4	24	0.7087	2.17	0.3938
BL x S/KB			(Error Term for BL and BL x KB)			

* Significant at p = 0.05

where: dυ = number of dependent measures
df(H) = degrees of freedom for treatment effect
df(E) = degrees of freedom for error effect

U = Wilk's likehood ratio statistic

$$\frac{|E|}{|E+H|}$$, where :

| E | = determinant of sum of square and cross-products for error

| E + H | = determinant of the sum of squares and cross-products matrix for error, and sum of squares and cross-products matrix for treatment

Table 6. Testing Stage ANOVA Summary Table Using MAB as Dependent Measure

Source	df	SS	F	P
Between-Subjects				
Keyboard (KB)	1	27.22	4.17	0.0871
Subject (S)/KB	6	39.15		
Within-Subject				
Session-Block (BL)	4	0.85	0.36	0.8334
BL x KB	4	0.65	0.28	0.8902
BL x S/KB	24	14.1		
Total	39	81.97		

Table 7. Testing Stage ANOVA Summary Table Using MTB as Dependent Measure

Source	df	SS	F	P
Between-Subjects				
Keyboard (KB)	1	1701.58	0.08	0.7823
Subject (S)/KB	6	122173.83		
Within-Subject				
Session-Block (BL)	4	80920.89	45.77	0.0001 *
BL x KB	4	3825.50	2.16	0.1038
BL x S/KB	24	10607.46		
Total	39	219229.28		

* Significant at p = 0.05

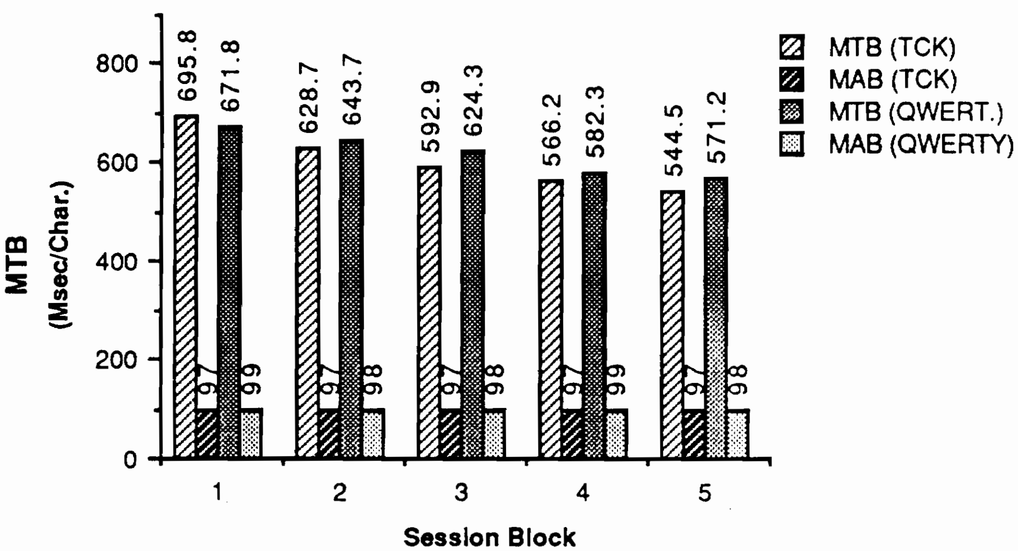
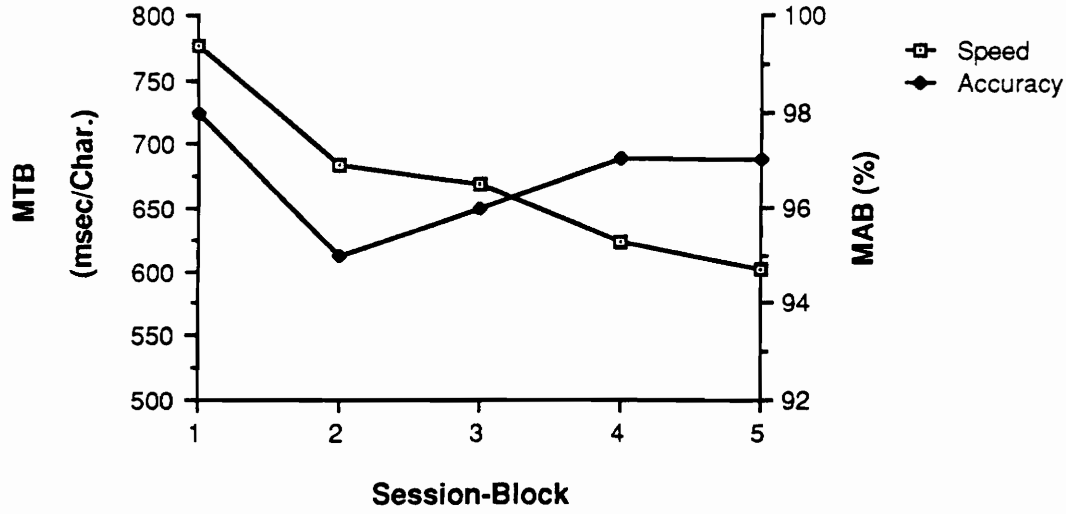
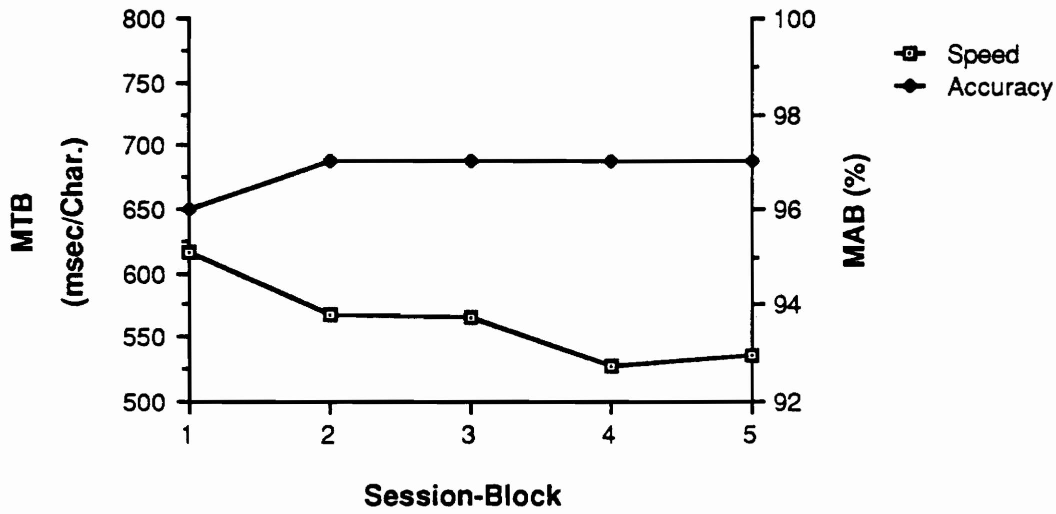


Figure 12. MTB and MAB by Session-Block for (a) QWERTY Group and (b) TCK Group (Averaged over all Subjects in each Group)

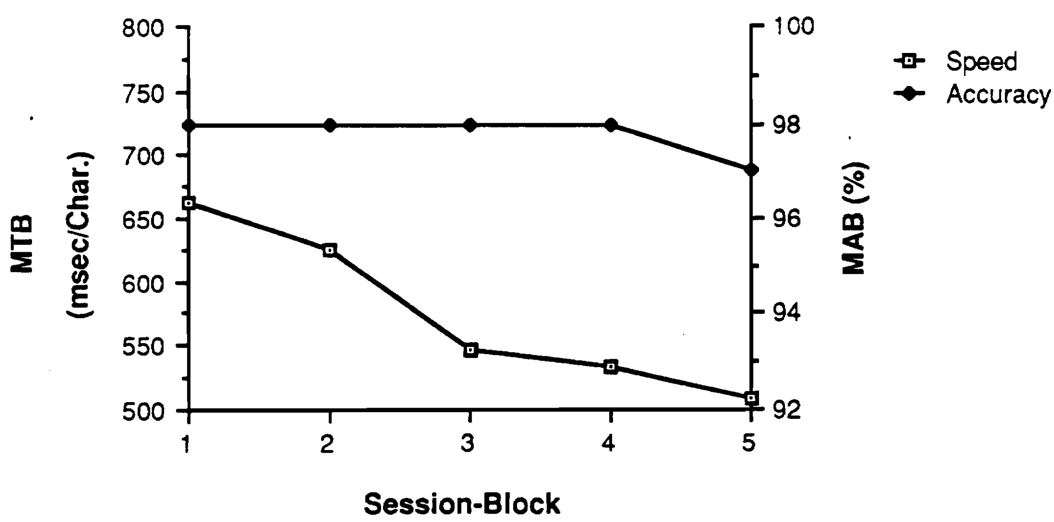


(a) Subject 1

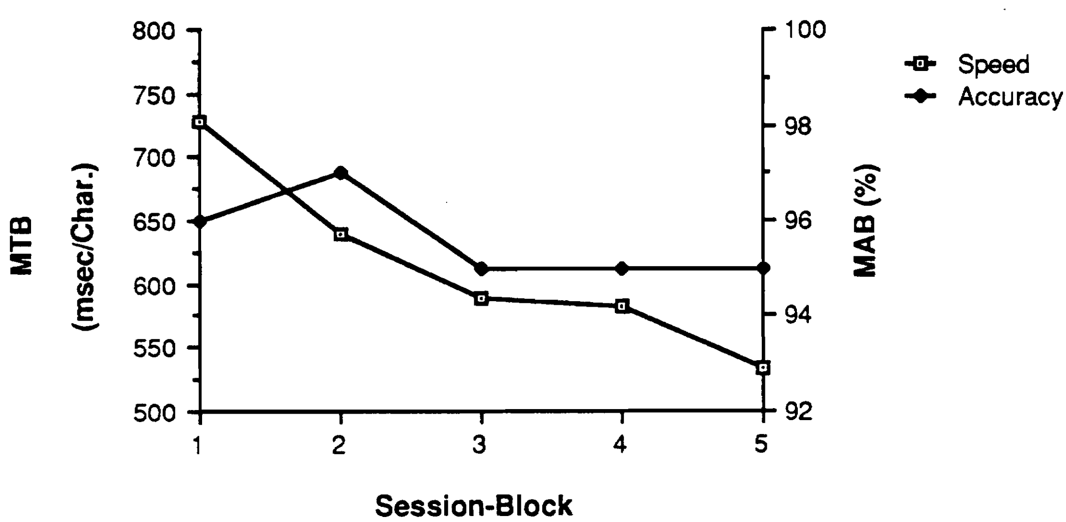


(b) Subject 2

Figure 13. MTB and MAB by Session-Block in the TCK Group : (a) Subject 1 and (b) Subject 2

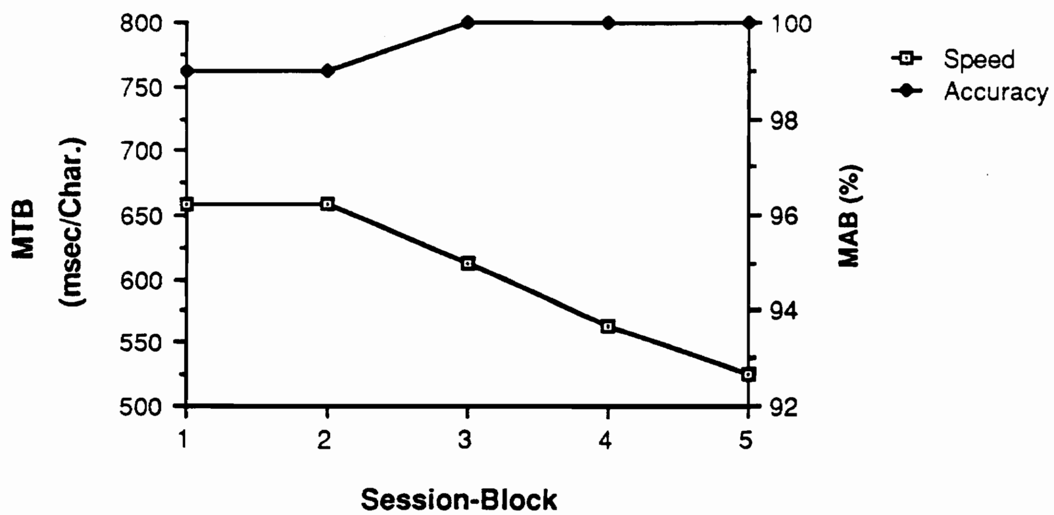


(a) Subject 3

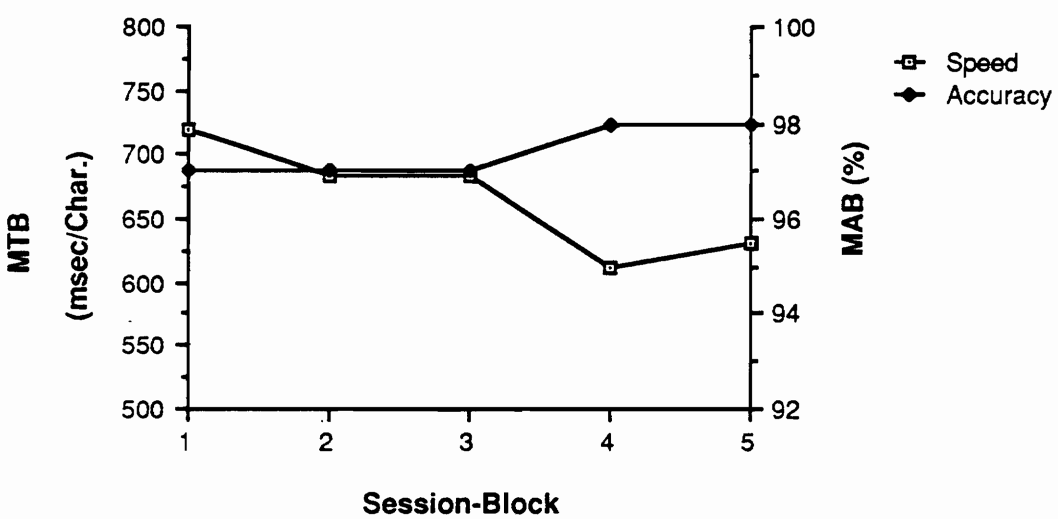


(b) Subject 4

Figure 14. MTB and MAB by Session-block in the TCK Group : (a) Subject 3 and (b) Subject 4

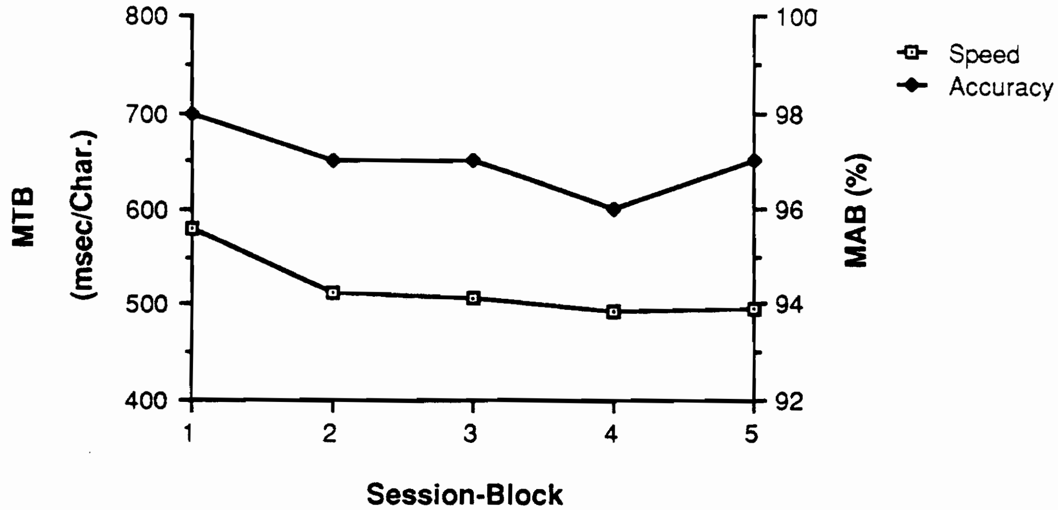


(a) Subject 1

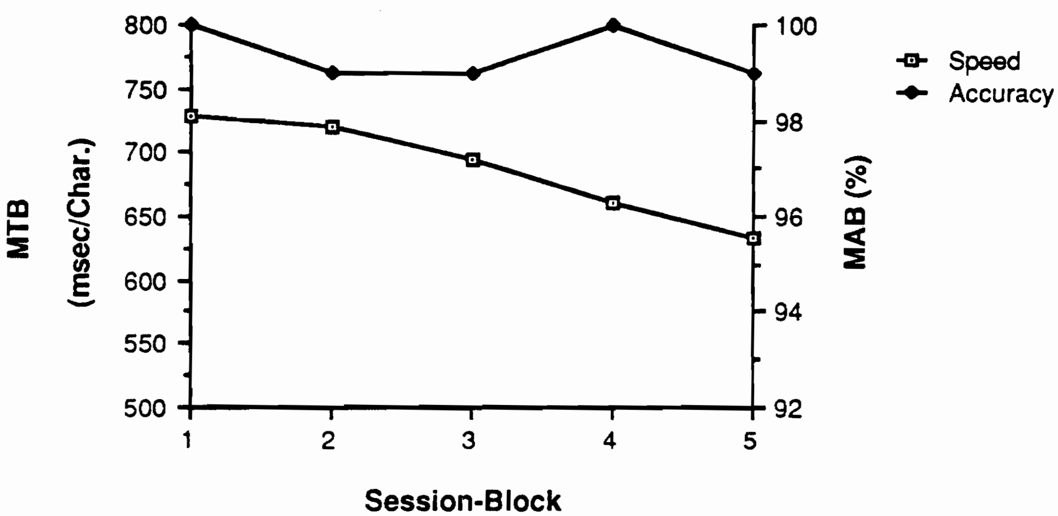


(b) Subject 2

Figure 15. MTB and MAB by Session-Block in the QWERTY Group : (a) Subject 1 and (b) Subject 2



(a) Subject 3



(b) Subject 4

Figure 16. MTB and MAB by Session-Block in the QWERTY Group : (a) Subject 3 and (b)Subject 4

Within-Group Analysis of the Testing Stage

As stated earlier, one of the purposes of setting typing performance criteria was to find out if there were any differences between the two groups in reaching the criteria. As shown in Figure 13, there were large discripencies in the number of training session among subjects of each group in reaching the criteria. For the TCK group, two subjects needed only five sessions, but the other two subjects took twenty sessions each. In the case of the QWERTY group, one subject needed only four training sessions, two subjects eight sessions, but one subject twenty-one sessions to reach the criteria. This raised the question of whether the performance of subjects within each group was significantly different at the testing stage knowing that there was a between-subjects difference in the number of training sessions to reach the criteria.

To approach the above issue, subjects within each group were divided into subgroups according to the number of training sessions taken to reach the criteria. A new factor was developed for each group that took into account the number of training sessions received to reach the criteria. The new factor, sessions-to-criteria, its levels for each group, and the number of subjects assigned to each level are listed in Table 8. For the TCK group, sessions-to-criteria had only two levels, low and high with two subjects assigned to each level. In the case of the QWERTY group, there were three levels of sessions-to-criteria, low, moderate, and high with one subject in the low level, two in the moderate, and one in the high level.

The analysis was based on data collected during the testing stage. For the TCK group, the experimental design was a 2x5 mixed-factor design. The design involved two independent variables : sessions-to-criteria and session block. Sessions-to-criteria is a fixed-

Table 8. Sessions-to-Criteria Factor and its Levels for each Group

Group	Session-to-criteria	Number of Subjects	# of Sessions To Crit.
TCK	Low	2	5
TCK	High	2	20
QWERTY	Low	1	4
QWERTY	Moderate	2	8
QWERTY	High	1	21

effects, between-subjects variable with two levels: low and high. Session block is fixed-effects, within-subject variable with five levels: session block 1, 2, 3, 4, and 5 (see Figure 17).

For the QWERTY group, the experimental design is an unbalanced 3x5 mixed-factor design. Sessions-to-criteria is a fixed-effects, between-subjects variable with three levels: low, moderate, and high. Session block is also a fixed-effects, within-subject variable with five levels : session block 1, 2, 3, 4, and 5 (see Figure 18).

A multivariate analysis of variance procedure was performed on the TCK design. The two independent variables were, as before, MTB and MAB. Table 9 is a complete MANOVA summary table. Session block was the only effect revealed significant, $F(4,8) = 35.4$, $p = 0.002$.

In the case of the QWERTY design, a MANOVA procedure was not possible due to insufficient error degrees of freedom and due to the unbalanced design. Instead, two univariate unbalanced analyses of variances were done, one for each dependent variable. Tables 10 and 11 are the ANOVA summary tables using the MTB and the MAB as dependent measures, respectively. The only significant effect revealed was the session block, $F(4,4) = 37.71$, $p = 0.002$ when using MTB as dependent measure. Note that session block was not significant in the design that used MAB as a dependent measure.

Session-to-criteria

Session-block		Low	High
	1	S: 1,2	S: 3,4
	2	S: 1,2	S: 3,4
	3	S: 1,2	S: 3,4
	4	S: 1,2	S: 3,4
	5	S: 1,2	S: 3,4

Figure 17. TCK Group Analysis Experimental Design Matrix. One Factor Within-Subject Design

Session-to-criteria

Session-block	Low	Moderate	High
1	S: 1	S: 2,3	S: 4
2	S: 1	S: 2,3	S: 4
3	S: 1	S: 2,3	S: 4
4	S: 1	S: 2,3	S: 4
5	S: 1	S: 2,3	S: 4

Figure 18. QWERTY Group Analysis Experimental Design Matrix. One Factor Within-Subject Design

Table 9. TCK Group Analysis MANOVA Summary Table

Source	dv	df(H)	df(E)	U	F	P
Between-Subjects						
Sess.-to-criteria (SC)	2	1	2	0.0323	14.97	0.179
Subject (S)/SC				(Error Term for SC)		
Within-Subject						
Session-Block (BL)	2	4	8	0.0517	5.94	0.002 *
BL x SC	2	4	8	0.4797	1.4	0.630
BL x S/SC		(Error Term for BL and BL x SC)				

* Significant at p = 0.05

where: dv = number of dependent measures
df(H) = degrees of freedom for treatment effect
df(E) = degrees of freedom for error effect

U = Wilk's likehood ratio statistic

$$\frac{|E|}{|E+H|}$$, where :

| E | = determinant of sum of square and cross-products for error

| E + H | = determinant of the sum of squares and cross-products matrix for error, and sum of squares and cross-products matrix for treatment

Table 10. QWERTY Group Analysis ANOVA Summary Table Using MAB as Dependent Measure

Source	df	SS	F	P
Between-Subjects				
Sess.-to-criteria (SC)	2	16.95	0.85	0.609
Subject (S)/SC	1	10.00		
Within-Subject				
Session-Block (BL)	4	0.6615	0.66	0.650
BL x SC	8	3.80	1.90	0.279
BL x S/SC	4	1.0		
Total	19	32.55		

* Significant at p = 0.05

Table 11. QWERTY Group Analysis ANOVA Summary Table Using MAB as Dependent Measure

Source	df	SS	F	P
Between-Subjects				
Sess.-to-criteria (SC)	2	85597.774	37.49	0.1147
Subject (S)/SC	1	1141.69		
Within-Subject				
Session-Block (BL)	4	28248.87	37.71	0.002 *
BL x SC	8	4093.30	2.80	0.167
BL x S/SC	4	731.601		
Total	19	119813.25		

* Significant at p = 0.05

Subjective Rating Stage

At the end of the experimental stage, each subject in each group responded to seven bipolar subjective rating scales addressing the keyboard that the subject had been using. Each scale had seven intervals. The responses (check marks on scales) to each of the seven-anchor scale were translated into numerical responses (1 to 7). Although correlations might exist between some of the seven scales of each group, all matched-pairs were treated independently. This approach allowed the analysis of the special areas of interest which some individual scales uniquely addressed (e.g., muscle fatigue, keyboard layout), rather than analyzing an overall satisfaction response if the answers were pooled together.

Since data collected from the bipolar scales cannot be considered as being on an interval scale, nonparametric statistical tests were employed. A Kolmogorov-Smirnov two-sample test (two-tailed) was performed for each pair of matched scales. Table 12 lists the results of each K-S test of pair of matched scales. The only scale that was found significantly different between the two groups was scale number 6 (ease of key operation), $KD = 4$, $p < 0.01$.

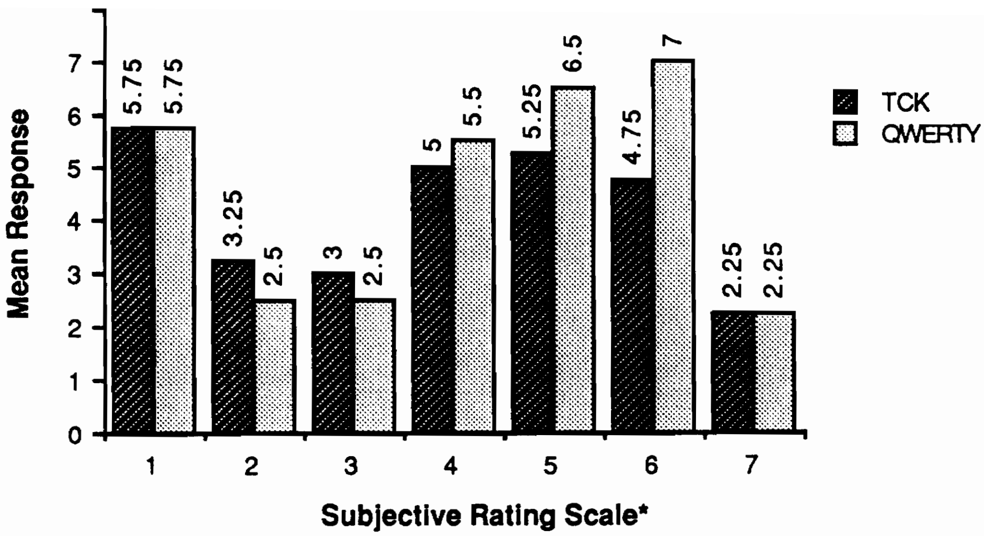
Figure 19 shows a comparison between the mean response to each scale for both groups. The figure depicts the discrepancy in mean response between the two groups to scale number 6 (TCK = 4.75, QWERTY = 7), which was found statistically significant after employing the K-S test. Possible reasons leading to this finding are presented in the Discussion section.

Table 12. Kolmogorov-Smirnov 2-Sample Test on Subjective Rating Response for each Pair of Matched Scales

Scale	K_D	Prob.
1	0	> 0.01
2	1	> 0.01
3	1	> 0.01
4	1	> 0.01
5	1	> 0.01
6	4	< 0.01 *
7	0	> 0.01

* significant at p= 0.01

Where K_D is the largest difference between the two cumulative distributions; N1 = N2 = 4



* Scale Topic: 1. Remembering key location/chords
2. Getting familiar with keyboard
3. Using the keyboard
4. Key location
5. Muscle fatigue
6. Key activation
7. Overall rating

Figure 19. Mean Response by Subjective Rating Scale (Range of Response, 1 to 7)

Discussion

Practice Stage

The analysis of this stage was brief since the primary objective of the study was to compare typing tasks instead of single-letter input tasks. However, the reaction to single letter stimuli gives valuable information about the difficulty of the chord under consideration.

The task is to respond to a single letter, randomly drawn from the total set, presented on the computer screen. Recorded task performance allows valid comparison between letter chords because each letter has an equal chance of occurrence and is presented uniquely on the screen. On the other hand, a comparison between chords based on a typing task is more difficult to conduct due to many factors. When text is presented as a task stimulus, some of the factors that might constrain the conduct of chord analysis are:

(a) Text content. Execution of chords in response to an "easy to read" text stimulus (such as text from a fourth grade English book) is presumably different than the execution of chords in response to a "hard to read" text (such as a research report on abstract mathematics).

(b) Average word length. Words in text vary in length and therefore the execution of chords of letters constituting these words might vary in their ease (or difficulty) of execution with respect to the length of the word.

(c) Frequency of occurrence of letters in the text. Letters within text vary in their frequency of occurrence. This results in a different total number of executions among chords which lead to an unbalanced training in executing various chords.

(d) The order of occurrence of letters within words. The ease of executing various chords might be affected by the order of occurrence of those chords within words. For example, reaction time to execute the first letter "a" in the word "accuracy" might be different from that of the second letter "a".

The statistical tests revealed no significant difference between each of the 15 letters used in the practice stage. However, from the plot of MTP and MAP by letter (Appendix H), some suggestions can be drawn.

It was assumed that letters assigned to chords that are considered "easy" to perform (e.g., executed by fingers with high pushing-force, unidirectionally and symmetrically), would yield faster reaction times and higher accuracy. This hypothesis cannot be totally supported. For example, the chord-pattern of the letter "E" was expected to be the easiest to execute since it was assigned to the strongest fingers (the two index fingers) and executed in a symmetrical and unidirectional fashions. However, this chord yielded a higher MTP and a lower MAP than those of the letter "I" which was executed using the weakest two fingers (the two little fingers) and in a unidirectional and symmetrical fashion (MTP and MAP for the letter "E" were 1182.6 msec and 96 %; for "I", 1085.6 msec and 98 %, respectively, with no statistically significant differences revealed). Similar exceptions to the chord coding scheme guidelines can be observed in the plot. Also, the figure suggests a negative relationship between speed and accuracy of execution of chords (higher speed is associated with decreased accuracy).

A closer analysis of the speed and accuracy of execution of each chord, individually and with respect to other chords, is needed to allow a thorough explanation of the existing relationships. This analysis, which is beyond the scope of this study due to the insufficient gathered information, would aid in explaining the perceptual and motoric difficulties of individual chords and would be part of the process of reaching an optimal coding of the TCK. Some possible analyses that can be conducted include a detailed error analysis of chord execution, and performance comparison between letters when assigned to the same chords. This latter analysis would be a way to check whether or not letters have inheritent differences in their perceptual difficulty.

Note that one cannot conclude that the coding scheme implemented in this study was completely invalid since data were collected shortly after the introduction of the TCK to subjects. Therefore, results might be highly affected by the unfamiliarity of subjects with the new keyboard. The finding that subjects, in both groups, never referred to the Help mode after few practice sessions is an indication that it was easy for subjects to remember a set of 17 chords or key locations within a short period of time, i.e., after inputing a total of 2600 letters each.

Training Stage

Setting performance criteria served two purposes : (a) allow to compare the number of training sessions needed to reach the criteria, and (b) assure that all subjects were at the same typing proficiency level before starting the testing stage.

For both keyboards, there was a very high between-subject variability in reaching the criteria. For the QWERTY keyboard, this could be attributed to the fact that some subjects were already somewhat more familiar with the keyboard before participating in the experiment; the average usage of computers/typewriters per week varied between subjects. Also, intrapersonal characteristics might be another contributing factor. For the TCK, variability in the number of training sessions cannot be explained by the between-subjects variability in prior familiarity with computers or typewriters since the TCK uses a totally new data entry concept. However, TCK key layout and design are possible contributors to the variability. Each key on the TCK was assigned to one finger. The execution of chords required simultaneous activation of two keys, thus concurrent movement of two fingers, which had to be placed on top of their respective keys for proper chord execution. The specific key layout and keyboard design might have put some constraints on some of the subjects with certain hand and finger characteristics (anthropometric and biomechanical) in executing some or all chords and ultimately affected their performance. For example, people with very short fingers could have had problems placing their fingers on top of all eight keys (this was noticed with one of the female subjects).

Another possible explanation of the between-subjects variability in reaching the criteria, for both keyboards, is the fact that subjects had to reach two performance criteria (speed and accuracy) jointly. For example, if in a certain training session a subject emphasized speed over accuracy and reached the speed criterion but not the accuracy criterion, that subject was not considered ready for the "testing stage". Both criteria had to be met in the same training session. Therefore, subjects had to make adjustments between speed and accuracy of typing in order to reach both criteria jointly. For example, subject 2 in the TCK group first reached the speed criterion in the 13th training session, but did not achieve the accuracy criterion. Therefore, the subject had to continue until both criteria were met in the same session (20th session). Note that subjects were not informed about the existence of the criteria, but were simply instructed "to type as fast and as accurately as possible, both speed and accuracy of typing are important.

Testing Stage

From both the MANOVA and the ANOVA procedures, the only effect revealed significant was session block (Tables 5, 6 and 7). This result was anticipated knowing that subjects gained more practice in using the keyboard from one session to another. However, from the ANOVA procedures it was found that the MTB was the major contributor to the source of variation of the session block effect. This can also be observed in the plots of MTB and MAB by session block for both groups and for individual subjects. Note that numerically the MTB for the TCK group were almost always lower than those of the QWERTY group (but not statistically significant), whereas, the MAB for the TCK were constantly lower than those of the QWERTY group (Figure 12). This suggest that the execution of chords on the TCK might be slightly faster than the execution of a single key on the QWERTY, nevertheless with less accuracy. Lower accuracy of typing in the TCK can be contributed to the key design and layout constraints, discussed earlier, and was possibly due to problems with the chord coding strategy adopted.

For each keyboard, accuracy (MAB) was almost constant for each session-block. This finding was also confirmed by the group analysis results. When MAB was used as an independent variable in the ANOVA of the QWERTY group, no significant effect was revealed for session block. In the TCK group, the MAB was exactly the same for each session block. This suggests that an asymptotic level of typing accuracy may be faster to achieve than an asymptotic level of typing speed. Similar suggestion can be made from the results of the ANOVA procedures discussed earlier.

Subjective Rating Stage

The subjective ratings served two objectives : (a) to allow a comparison of keyboard characteristics, and (b) to help obtain information that could be used in improving features of the TCK.

Scale 6 (ease of operating keys on the QWERTY keyboard and chords on TCK) was the only pair of matched scales that were found significantly different. This result was expected since activating a single binary key is obviously easier than simultaneously activating two ternary keys. Furthermore, the the design configuration of the ternary key was preliminary and not based on research. In fact, the top of the ternary key did not provide enough resistance against the fore/aft motion of the finger activating it: the finger tended to slide off. Such design deficiencies are likely to affect the proper execution of chords, and should be noticable to the operator.

For the TCK (as well as for the QWERTY keyboard), subjects expressed that it was a fairly easy task to remember a set of 17 characters and their corresponding chords. Apparently, it was fairly easy to adapt to the new TCK concept. No serious discomforts or muscle fatigues were encountered by subjects over the whole period of participation. The subjects gave an almost excellent rating of the TCK keyboard in terms of its potential use and application.

General Discussion

Performances of the two groups of subjects on the TCK and on the QWERTY keyboard were comparable in many ways. To acquire chord typing skill does not seem to be more difficult than, or different from, to learn of common touch typing. Both skills have memory and retrieval requirements. In touch typing, typists have to memorize and retrieve key locations that are associated with characters, whereas, in ternary chord typing, typists associate chord-patterns with characters. The exact relative perceptual difficulty between the two skill components (i.e., memorizing and retrieving chords as compared to memorizing and retrieving key locations) is yet to be determined.

The psychomotoric (motoric) requirements of each typing type are quite different. When touch typing, the control action of of each finger is to push down on one key to produce one character. In the case of ternary chord typing the motoric requirements are more complex. Two fingers have to be simultaneously moved in either fore, aft, fore/aft, or aft/fore directions. This might create problems if associated involuntary movement of fingers that are not involved in executing the chord activates other keys, which would result in erroneous inputs. This brings up an important issue: key design and layout.

It was apparent that the design of the ternary keys was not optimized to maximize performance. An evaluation of the current design of keys and their layout on the keyboard is essential for providing better control over key movement and chord execution.

Apparently, the use of a set only of 17 characters did not place heavy memory, retrieval, or motoric loads on subjects of both groups. However, if the number of characters is increased, the relative impact of factors affecting each typing skill may differ and in turn performances on each keyboard might not agree with results of this study.

Conclusions

The results of this study can be summarized as follows:

- Performances on both keyboards, TCK and QWERTY, were comparable in all stages of the experiment. No significant difference was revealed for the keyboard effect.

- Nevertheless, executing chords on the TCK was rated significantly more difficult than activating keys on the QWERTY keyboard.

- Subjects adapted to the new keyboard in fairly short time and accepted it as a potential data entry device.

- A set of 17 chords can be memorized in less than 2 hours.

Although this work contributes to the body of knowledge concerning the TCK, much work in the area remains to be done. Extensive experimental work is needed to develop optimal chord coding and design configuration of the TCK. The chord coding should be expanded to accommodate at least 39 characters (36 alphanumeric, space, comma, and a period). Anthropometric and biomechanical characteristics of potential users of the TCK should be used as driving guidelines to help achieve an optimal design of the device. Also, further research is needed to fully explain and define skill requirements, perceptual and motoric, of ternary chord typing.

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Appendix A. Subjective Rating Instructions and Scales

INSTRUCTION FOR TERNARY CHORD KEYBOARD RATING SCALES

Following these instructions, you will be asked to judge different features of the keyboard based on a series of descriptive rating scales.

Here is an example of how to use the rating scale:

If you feel that your judgment about remembering the key combinations (chords) was closely related to one end of the scale, you should place your check-mark as follows:

```
  Very    --X--¦-----¦-----¦-----¦-----¦-----¦----- Very
Difficult                                           Easy
```

or

```
  Very    -----¦-----¦-----¦-----¦-----¦-----¦--X-- Very
Difficult                                           Easy
```

If your judgment about remembering the key combinations is QUITE CLOSELY related to one end of the scale (but not extremely), you should place your check-mark as follows:

```
  Very    -----¦--X--¦-----¦-----¦-----¦-----¦----- Very
Difficult                                           Easy
```

or

```
  Very    -----¦-----¦-----¦-----¦-----¦--X--¦----- Very
Difficult                                           Easy
```

If your judgment about remembering the key combinations is ONLY SLIGHTLY RELATED to one end of the scale (but not really neutral), then you should check as follows:

```
  Very    -----¦-----¦-----¦-----¦--X--¦-----¦----- Very
Difficult                                           Easy
```

or

```
  Very    -----¦-----¦--X--¦-----¦-----¦-----¦----- Very
Difficult                                           Easy
```

If your judgment about remembering the key combinations is NEUTRAL between the ends of the scale, or if you consider the scale to be COMPLETELY IRRELEVANT, you should then place your check-mark in the middle space as follows:

```
Very   -----|-----|-----|--X--|-----|-----|----- Very
Easy                                             Difficult
```

Note that the very difficult/very easy scale is one example of those that you will be given. There will be five different scales on which you will provide your rating.

IMPORTANT

1. Place your check-mark (or X-mark) IN THE MIDDLE OF SPACES, not on the boundaries:

```
                  This             Not This

Very  -----|-----|--X--|-----|------X-----|-----  Very
Easy                                              Difficult
```

2. Be sure to check every scale . DO NOT OMIT ANY SCALES.

3. Never put more than one check-mark on a single scale.

4. IMPORTANT. Do not look back and forth through the rating scales.

MAKE EACH SCALE ITEM A SEPARATE AND INDEPENDENT JUDGMENT

5. Work at fairly high speed through these ratings. Do not worry or puzzle over individual items. It is your first judgment that is needed. Please do not be careless, because Your ACTUAL an HONEST FEELINGS are necessary.

For each of the following scales, place your check-mark in the appropriate position.

1. How easy was it to remember the key combinations (chords)?

```
  Very    -----|-----|-----|-----|-----|-----|----- Very
Difficult                                           Easy
```

2. Getting familiar with using the keyboard was:

```
  Very    -----|-----|-----|-----|-----|-----|----- Very
  Easy                                            Difficult
```

3. Using the keyboard was:

```
  Very    -----|-----|-----|-----|-----|-----|----- Very
Comfortable                                      Uncomfortable
```

4. The keyboard layout (key locations) was:

```
  Very    -----|-----|-----|-----|-----|-----|----- Excellent
  Poor
```

5. During each session, muscle fatigue was:

```
  Maximal -----|-----|-----|-----|-----|-----|----- Minimal
```

6. In combinations (in chords), the KEYS were:

```
 Very Hard -----|-----|-----|-----|-----|-----|----- Very Easy
To Activate                                          To Activate
```

7. Give your overall rating of this keyboard (in terms of its potential use and application):

```
Excellent  -----|-----|-----|-----|-----|-----|----- Very
                                                     Poor
```

INSTRUCTION FOR QWERTY KEYBOARD RATING SCALES

Following these instructions, you will be asked to judge different features of the keyboard based on a series of descriptive rating scales.

Here is an example of how to use the rating scale:

If you feel that your judgment about remembering the key combinations (chords) was closely related to one end of the scale, you should place your check-mark as follows:

Very Difficult --X--|-----|-----|-----|-----|-----|----- Very Easy

or

Very Difficult -----|-----|-----|-----|-----|-----|--X-- Very Easy

If your judgment about remembering the key combinations is QUITE CLOSELY related to one end of the scale (but not extremely), you should place your check-mark as follows:

Very Difficult -----|--X--|-----|-----|-----|-----|----- Very Easy

or

Very Difficult -----|-----|-----|-----|-----|--X--|----- Very Easy

If your judgment about remembering the key combinations is ONLY SLIGHTLY RELATED to one end of the scale (but not really neutral), then you should check as follows:

Very Difficult -----|-----|-----|-----|--X--|-----|----- Very Easy

or

Very Difficult -----|-----|--X--|-----|-----|-----|----- Very Easy

If your judgment about remembering the key combinations is NEUTRAL between the ends of the scale, or if you consider the scale to be COMPLETELY IRRELEVANT, you should then place your check-mark in the middle space as follows:

```
Very    -----|-----|-----|--X--|-----|-----|----- Very
Easy                                               Difficult
```

Note that the very difficult/very easy scale is one example of those that you will be given. There will be five different scales on which you will provide your rating.

IMPORTANT

1. Place your check-mark (or X-mark) IN THE MIDDLE OF SPACES, not on the boundaries:

```
                 This          Not This

Very -----|-----|--X--|-----|------X-----|-----  Very
Easy                                             Difficult
```

2. Be sure to check every scale . DO NOT OMIT ANY SCALES.

3. Never put more than one check-mark on a single scale.

4. IMPORTANT. Do not look back and forth through the rating scales.

MAKE EACH SCALE ITEM A SEPARATE AND INDEPENDENT JUDGMENT

5. Work at fairly high speed through these ratings. Do not worry or puzzle over individual items. It is your first judgment that is needed. Please do not be careless, because Your ACTUAL an HONEST FEELINGS are necessary.

For each of the following scales, place your check-mark in the appropriate position.

1. How easy was it to remember the key locations of the 15 letters:

```
  Very    -----|-----|-----|-----|-----|-----|----- Very
Difficult                                           Easy
```

2. Getting familiar with using the keyboard was:

```
  Very    -----|-----|-----|-----|-----|-----|----- Very
  Easy                                          Difficult
```

3. Using the keyboard was:

```
  Very    -----|-----|-----|-----|-----|-----|----- Very
Comfortable                                    Uncomfortable
```

4. The keyboard layout (key locations) was:

```
  Very    -----|-----|-----|-----|-----|-----|----- Excellent
  Poor
```

5. During each session, muscle fatigue was:

```
  Maximal -----|-----|-----|-----|-----|-----|----- Minimal
```

6. The KEYS were:

```
 Very Easy -----|-----|-----|-----|-----|-----|----- Very Hard
To Activate                                          To Activate
```

7. Give your overall rating of this keyboard :

```
Excellent  -----|-----|-----|-----|-----|-----|----- Very
                                                     Poor
```

Appendix B. Informed Consent Form for Screening Procedure

INFORMED CONSENT FORM FOR SCREENING PROCEDURE

Before you are asked to participate as a subject in the research project, we ask that you complete a brief screening procedure. The purpose of this procedure is to determine whether your typing level meets the criteria we have established for participating in this experiment. This screening procedure is expected to take no longer than 20 minutes. If you pass the screening procedure, you will be asked to participate in the experiment. You will be paid $5 dollars for the time you spend in the screening procedure. You will also be paid if you participate in the experiment.

As a subject in this screening procedure you are entitled to the following rights:

1.) You may withdraw from participation in this procedure at any time you wish without any penalty. However, if you do so, you will not be asked to participate in the experiment.

2.) The principal investigator of this project will answer any questions you may have concerning this procedure, and you should not sign this consent form until you are satisfied that you understand all the terms involved.

3.) The research team members on this project include:
Fadi Fathallah, Graduate Student;and
Dr. Karl H. E. Kroemer, Faculty Member.

4.) The data collected during your participation will be treated with confidentiality and used solely for purposes of screening for the research project.

If you have further questions about your rights as a participant, you may contact Mr. Charles D. Waring, Chairman of the Institutional Review Board at Virginia Tech.

Your signature below indicate that you have read this document entirely, that your questions have been answered, and that you consent to participate in the screening procedure described.

The faculty and graduate students involve in this research appreciate your participation.

________________________ ________________________

Signature Telephone number

____

Printed name

Appendix C. Screening Procedure Instructions

INSTRUCTIONS FOR THE SCREENING PROCEDURE

The purpose of this procedure is to determine your typing performance level. You will be given an eight-line printed text to type using a computer keyboard.

The experimenter will demonstrate the features of the keyboard that you will be using and the task requirements. During and after the demonstration you may ask any questions that you have. The task will start immediately following the demonstration.

If you have any questions, please feel free to ask them at this time.

Appendix D. Screening Procedure Text Material

Jim is shooting off his firecrackers now, as you can hear. I wish that he had done so at his own home, for it is too much music for me. On his way to work one morning, Mr. Smith slipped on the ice and broke his leg. Several month went by before he was completely well and could see again. The doctor told Mr. Jones that if he had more exercise he could feel better, so he went to the gymnasium where he could get all the food he needed.

Appendix E. Screening Information Form

SCREENING TEST INFORMATION

subject :

========

date: age:

time: sex:

1. Average hours of computer/typewriter usage per week:__________

2. Hunt & peck ? : Y N

3. Fingers used: L R M I TH TH I M R L

4. Eyes on keys ? : Y N

5. Fingers on home row ?: Y N

6. Time to complete passage (minutes): ______________

7. GNWP (H & P) : ______________

8. Musical Instruments usage information:

Appendix F. Consent Form for Experiment

INFORMED CONSENT FORM FOR EXPERIMENT

You are asked to participate as a subject in a research project. The purpose of this experiment is to examine typing performance in response to some materials presented on a computer screen. You will be asked to learn the input code of several characters. You will input displayed combinations of these characters using a specified data entry device (keyboard).

The experiment is expected to last 10 to 15 days for a maximum of two hours per day. If you decide to participate, you will be paid $5 dollars per hour for the time you spend in the laboratory. Payment will be made upon completion of your participation.

As a subject in this experiment you are entitled to the following rights:

1.) You may withdraw from participation in this research project any time you wish without any penalty. However, if you do so, you will only be paid for the time which you actually spend in the experiment.

2.) The principal investigator of this project will answer any questions you may have concerning this procedure, and you should not sign this consent form until you are satisfied that you understand all the terms involved.

3.) The research team members on this project include:
Fadi Fathallah, Graduate Student;and
Dr. Karl H. E. Kroemer, Faculty Member.

4.) If you wish to receive a summary of the results of this research, please include your address (where you expect to be living in three months from now0 with your signature below. Please do so only if you are truly interested in seeing the results.

5.) The data collected during your participation will be treated with anonymity. After you have participated, your name will be separated from your data. For this reason, if you wish to withdraw your data from our analysis, you must notify the experimenter immediately after your participation is complete.

Since it will cause the researcher a great deal of inconvenience if you do not complete the entire study, please do not agree to participate in this study unless you can agree to cooperate in the manner described above.

If you have further questions about your rights as a participant, you may contact Mr. Charles D. Waring,

Chairman of the Institutional Review Board at VPI&SU
Your signature below indicate that you have read this document entirely, that your questions have been answered, and that you consent to participate in the experiment described.

The faculty and graduate students involve in this research appreciate your participation.

______________________ ______________________
Signature Telephone number

____
Printed name

Industrial Ergonomics Lab.
IEOR Department
VPI&SU
Blacksburg, VA 24061
(703)961-5359

Appendix G. Experiment Instructions (All Stages)

GENERAL INSTRUCTIONS

The purpose of this study is to analyze different types of data entry devices by examining typing performance. You will be entering some alphabetical data using a newly designed keyboard. The keyboard, called ternary chord keyboard, has only 8 keys (four keys per hand). Each key has three positions (ternary key): neutral, forward, and backward positions. To produce a character, two keys, one from each hand have to be simultaneously activated. Characters are assigned to different key combinations or chords.

The experiment will be divided into two main parts:

a) Single-letter stage. In this stage, you will learn the key combinations (chords) of several letters. You will participate in several sessions. In each session the main task is to respond to a single letter presented in the middle of the computer screen.

b) Typing stage. In this stage, your task is to type several lines of text presented on the screen using the ternary chord keyboard. You will be asked to participate in several typing sessions.

Preceding each part of the experiment you will be given a detailed demonstration of all elements involved in the task.

INSTRUCTIONS FOR SINGLE-LETTER STAGE

In this part of the experiment your task is to produce a key combination on the ternary chord keyboard that corresponds to a single letter displayed in the middle of the computer screen. You will participate in four sessions every day. Each session will last about 10 to 15 minutes with a five-minute break between each session.

The experimenter will give a demonstration session to help you become familiar with the task. During and after the demonstration you may ask any questions that you have. The experimental sessions will begin immediately following the demonstration session.

If you have any questions, please feel free to ask them at this time.

GENERAL INSTRUCTIONS

The purpose of this study is to analyze different types of data entry devices by examining typing performance. You will be entering some alphabetical data using a computer keyboard. The keys on this keyboard have no labels on them (blank keys).

The experiment will be divided into two main parts:

a) Single-letter stage. In this stage, you will learn the key locations of several letters. You will participate in several sessions. In each session the main task is to respond to a single letter presented in the middle of the computer screen.

b) Typing stage. In this stage, your task is to type several lines of text presented on the screen. You will be asked to participate in several typing sessions.

Preceding each part of the experiment you will be given a detailed demonstration of all elements involved in the task.

INSTRUCTIONS FOR SINGLE-LETTER STAGE

In this part of the experiment your task is to press key on the keyboard corresponds to a single letter displayed in the middle of the computer screen. You will participate in four sessions every day. Each session will last about 10 to 15 minutes with a five-minute break between each session.

The experimenter will give a demonstration session to help you become familiar with the task. During and after the demonstration you may ask any questions that you have. The experimental sessions will begin immediately following the demonstration session.

If you have any questions, please feel free to ask them at this time.

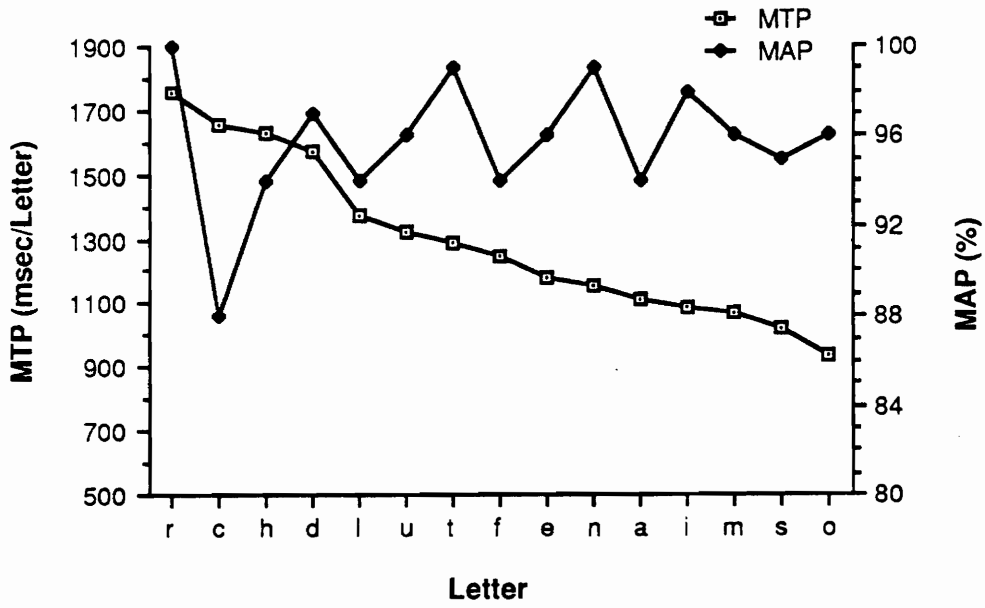
INSTRUCTIONS FOR TYPING STAGE

In this part of the experiment your task is to type several lines of text presented on the computer screen. You will be using the same keyboard you have been using. The text will consist only of words that are made up of different combinations of the 15 letters introduced in the first part of the experiment. The help mode is identical to the one you have used in earlier sessions. You will participate in four typing sessions every day. Each session will take 15 to 20 minutes with a five-minute break between each session.

The experimenter will give a demonstration session to help you become familiar with the task. During and after the demonstration you may ask any questions you have. The experimental trials will begin immediately following the demonstration session.

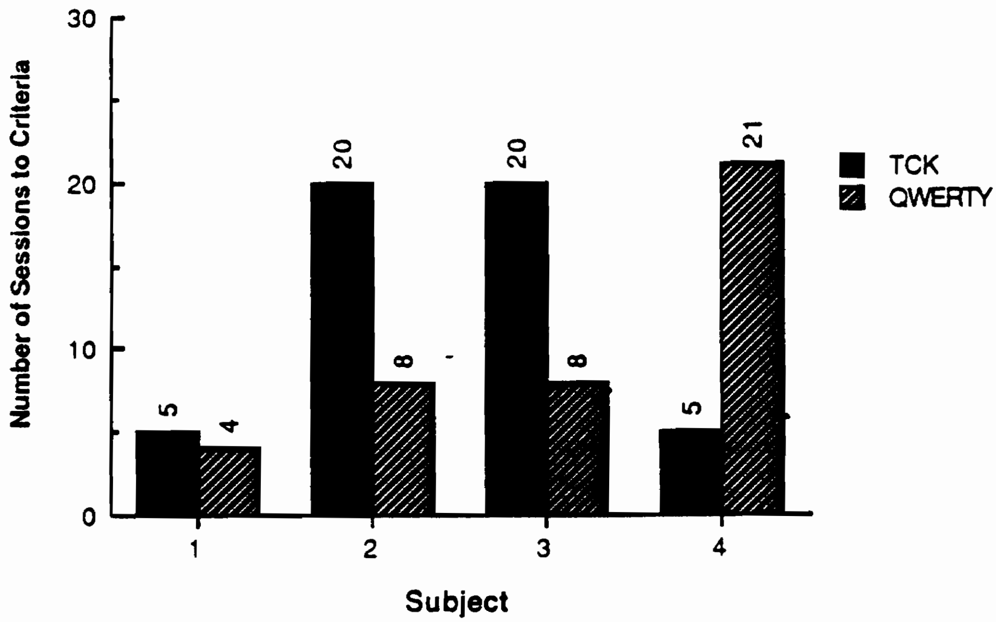
If you have any questions, please feel free to ask them at this time.

Appendix H. MTP and MAP Plot (TCK Group)



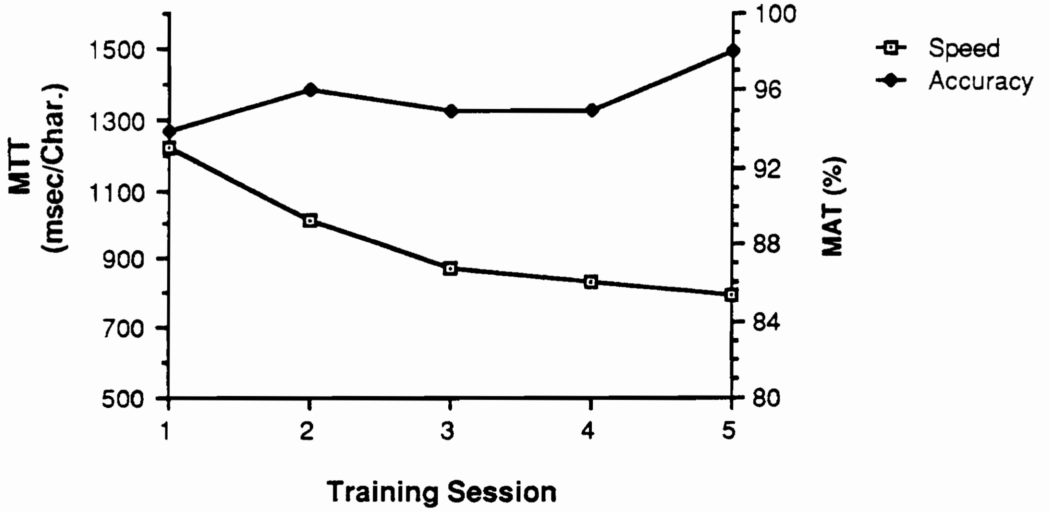
MTP and MAP by Letter (Averaged over all TCK Subjects)

Appendix I. Number of Training Sessions to Criteria Plot

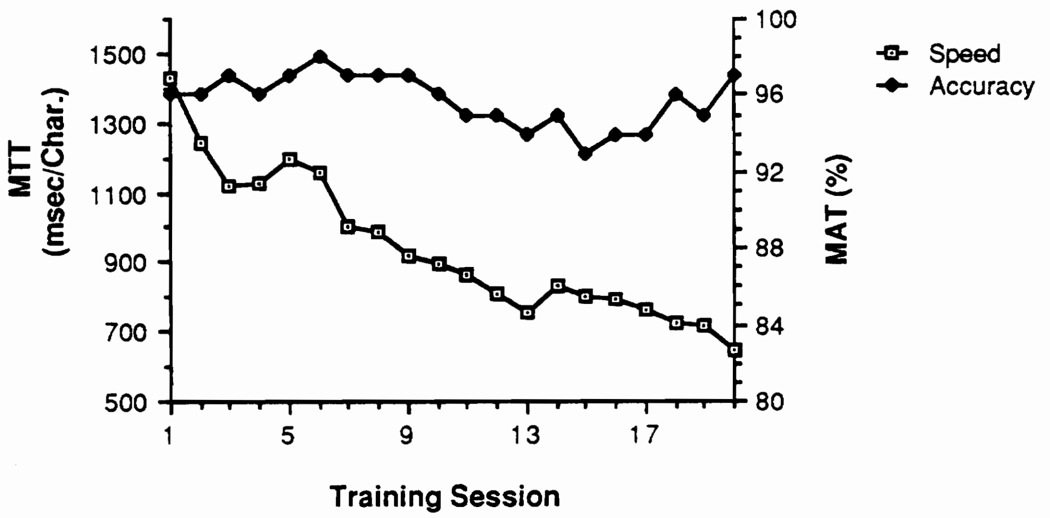


Appendix I. Number of Training Sessions to Criteria Plot

Appendix J. MAT and MTT Plots of each Subject

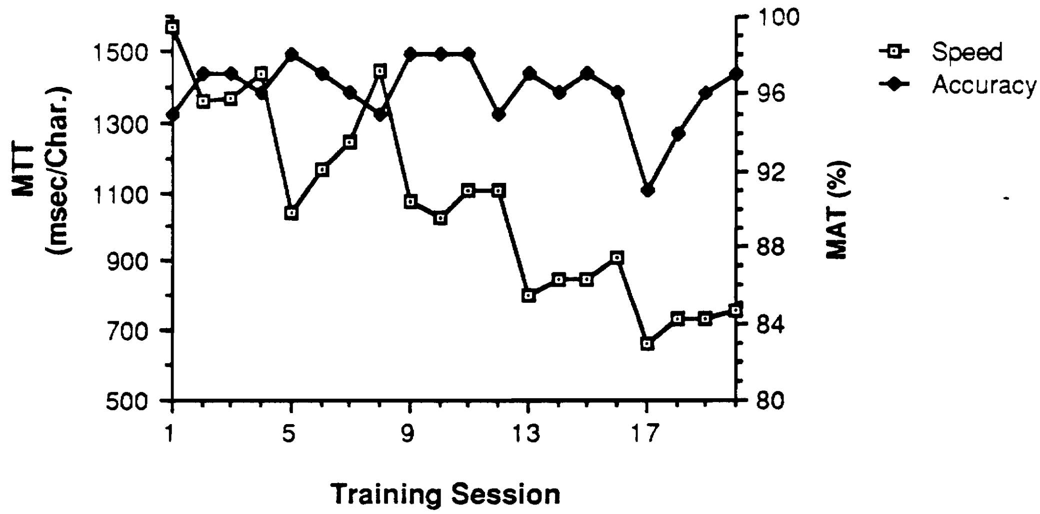


(a) Subject 1

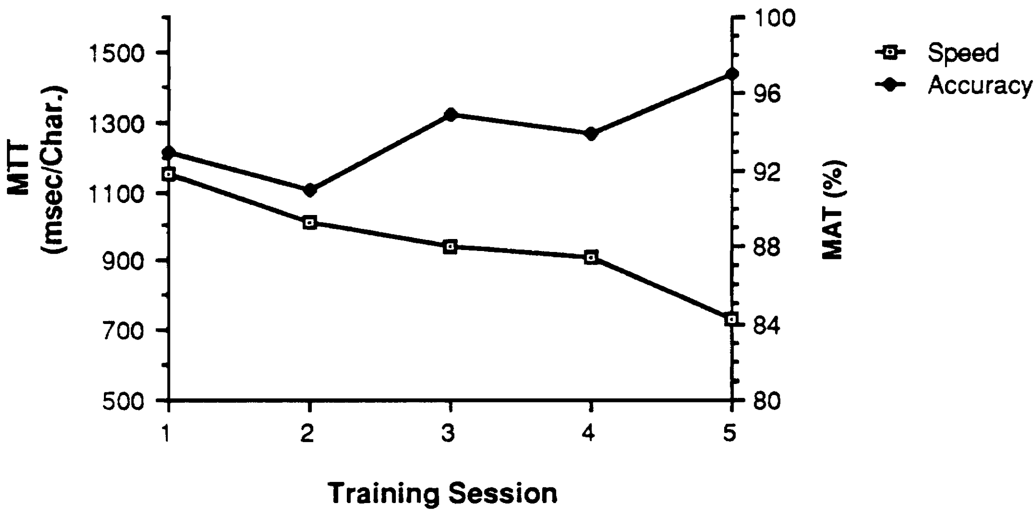


(b) Subject 2

MTT and MAT by Training Session in the TCK Group : (a) Subject 1 and (b) Subject 2

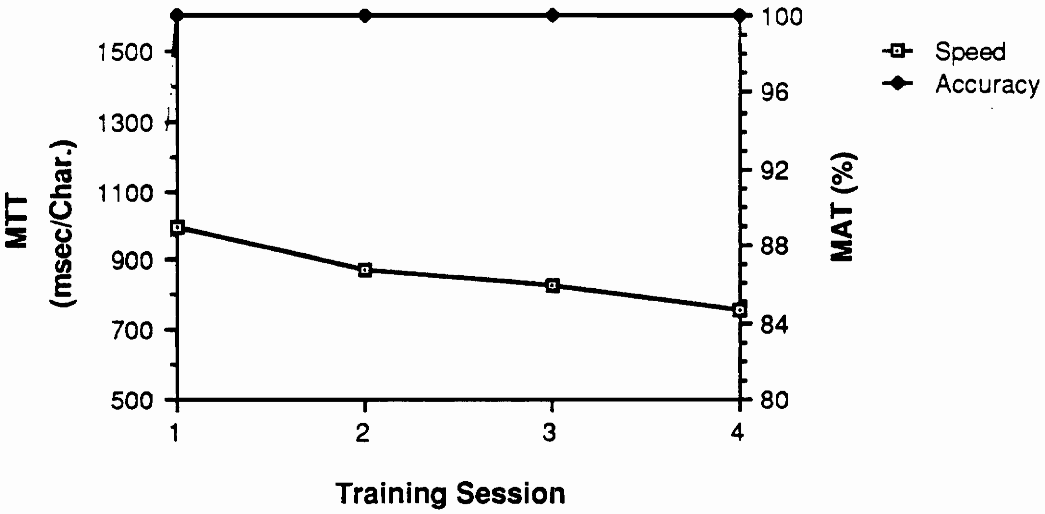


(a) Subject 3

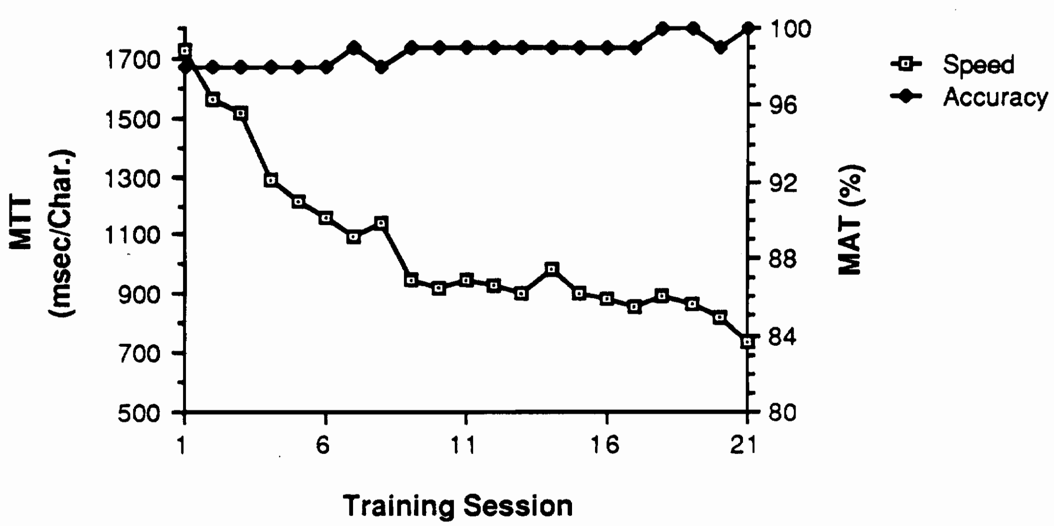


(b) Subject 4

MTT and MAT by Training Session in the TCK Group : (a) Subject 3 and (b) Subject 4

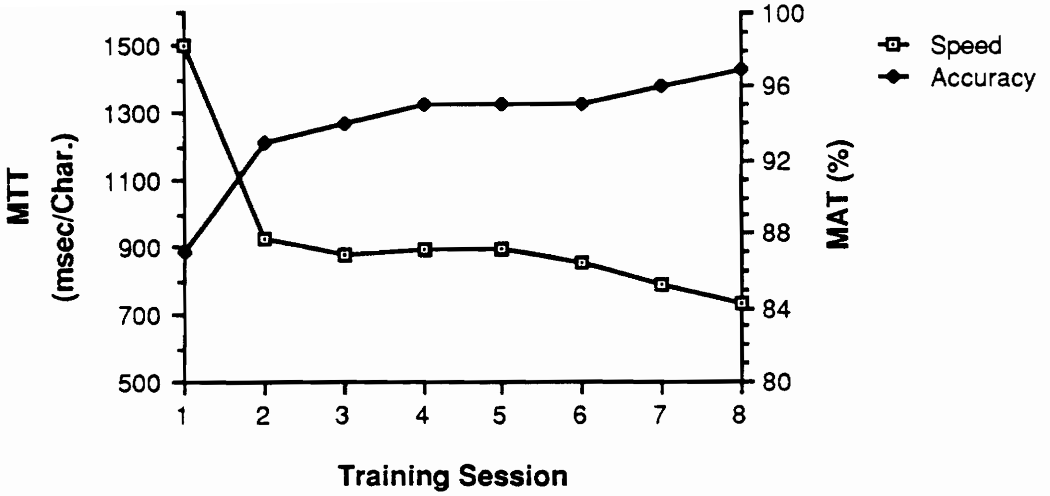


(a) Subject 1

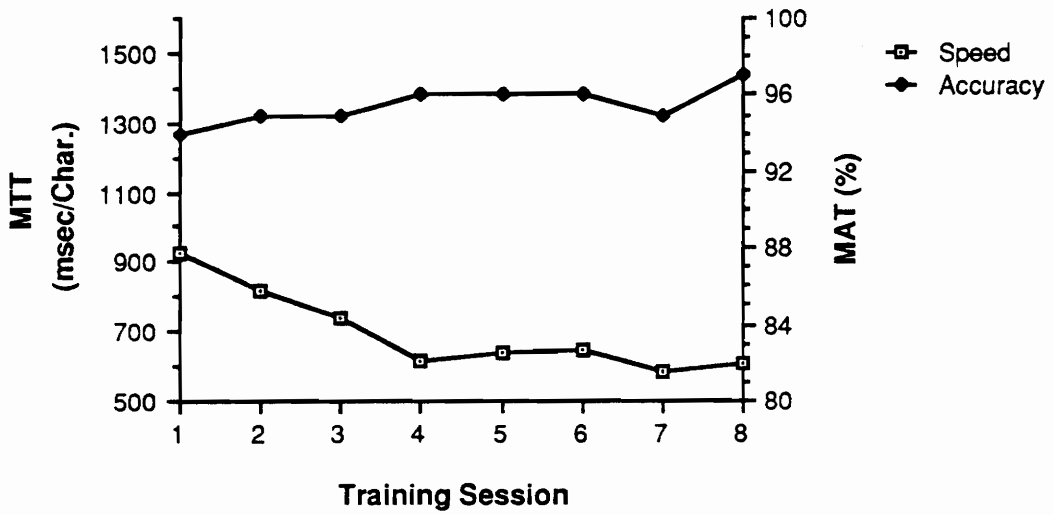


(b) Subject 2

MTT and MAT by Training Session in the QWERTY Group : (a) Subject 1 and (b) Subject 2



(a) Subject 3



(b) Subject 4

MTT and MAT by Training Session in the QWERTY Group : (a) Subject 3 and (b) Subject 4

Vita

Fadi Adnan Fathallah was born on December 8, 1963, in Beirut, Lebanon. He received a B.S. in Industrial Engineering from Texas Tech University in May of 1986. In Decmber of 1988, he earned a M.S. in Industrial Engineering and Operations Research from Virginia Polytechnic Institute and State University with a concentration in Human Factors Engineering. As a graduate student, he served as a teaching assistant in engineering psychology and methods of industrial engineering. He has also conducted research in the fields of human performance assessment and chord keyboards evaluation, and co-authored two publications related to these topics.

Fadi is a member of Tau Beta Pi, Alpha Pi Mu, and Golden Key national honor societies and was nominated to the National Dean's List for two consecutive years. Fadi is also a student member of the Human Factors Society.

Fadi Fathallah